Nuclear Astrophysics

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Theme and Scope of Nuclear Astrophysics

Nuclear Reactions in Cosmic Environments

H-Burning
He-Burning
C/O-Burning
Si-Burning
NSE
QSE
α-Process
r-Process
s-Process
p/γ-Process

Conceptual Description,
Detailed Modeling,
Parametrizations

Observations of
- *Nuclear Ashes*
- *Energetics, Spectra*

Stellar Interiors
Accretion
Novae
Supernovae
Energetic ISM
Cosmic Rays

Nuclear Astrophysics Aspects: Nuclear Physics

- Atomic Nuclei
  - Nuclear Binding Energy and its Decomposition
  - Models of the Nucleus: Droplet, ... Shells
- Nuclear Forces
  - Strong Interaction Models
  - Weak Interaction Models
- Nuclear Reactions
  - Regimes of Different Descriptions
  - Nuclear Reaction Models

Nuclear Astrophysics Aspects: Astro - Physics

- Stellar Structure and Evolution
  - Hydrostatic Conditions and Late-Stage Evolution
  - Mass Loss, Mass Accretion from Companions
- Star Formation and Final States
  - Star Formation: Dense Cores; Low to High-Mass Stars
  - Supernova Types and Models: Core Collapse; SNIa
- Cosmic Evolution Aspects
  - Recycling of Matter
  - Feedback and Evolution of Galaxies

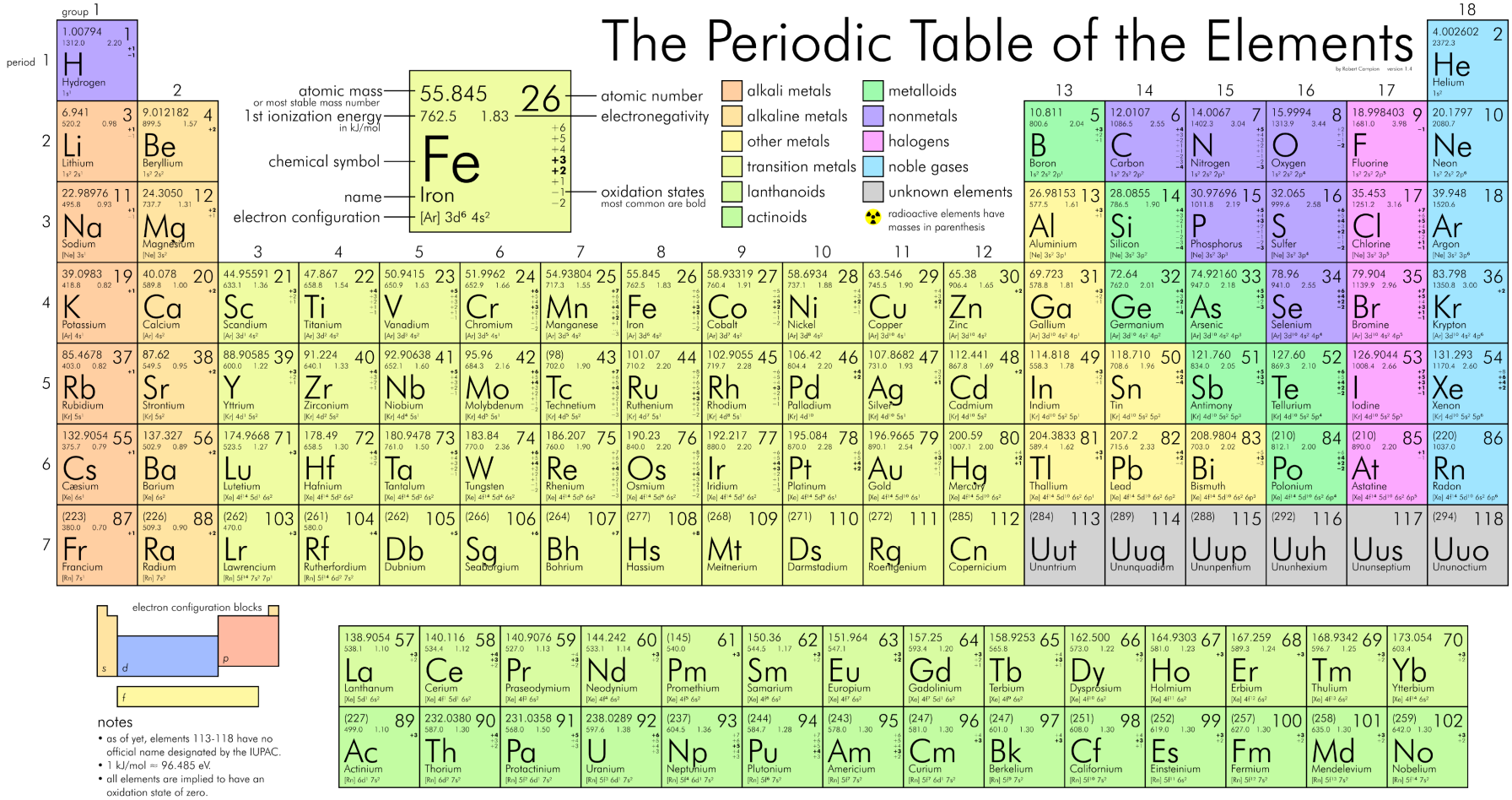
Terminology and Subtopics

- Elements and Isotopes
  - The Nuclide Landscape
  - Abundances
- Reactions between Nuclides
  - Geometrical and Nuclear Aspects; the S-Factor
  - Particle Populations; the Gamov Window
  - Nuclear Reaction Types
  - Equilibria
  - Nuclear Reaction Theory; R-and S-Matrix Theory
- Cosmic Plasma
  - States and Composition
  - Thermodynamics, Chemical Potential

Elements

Chemical Elements

- late 19th century: Group chemical elements according to their properties
  - Dmitri Mendeleev 1869 (and others)

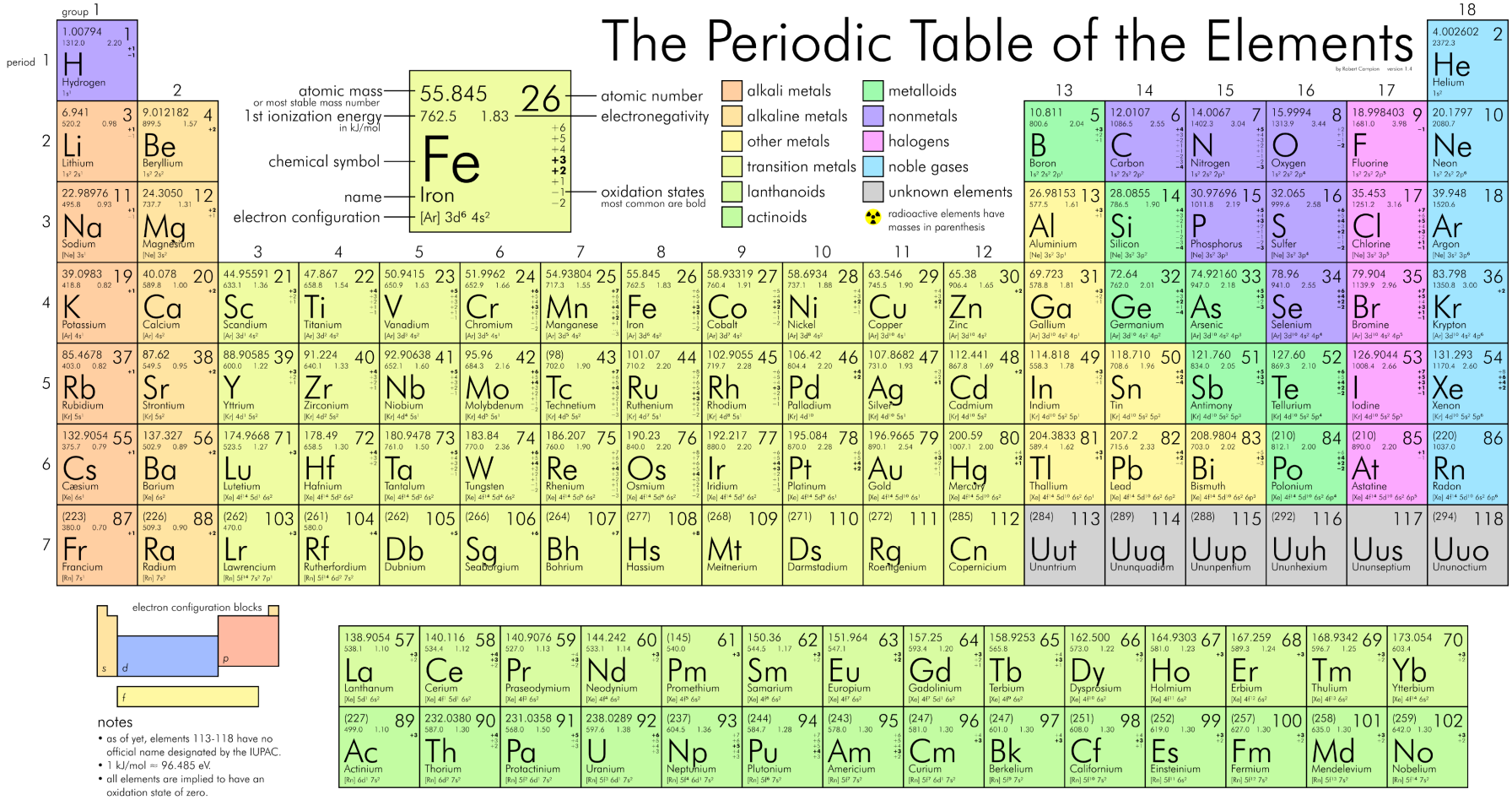


from: Wikipedia, 2013

Elements

Chemical Elements

- 98 different elements occur naturally on Earth (“stable” elements)
- Currently, 118 different elements are “known”



from: Wikipedia, 2013

Elements

Chemical Elements

- The systematics: chemical properties → Atomic electron-shell configuration (outer electrons)

1 (IA)	2 (IIA)	3 (IIIB)	4 (IVB)	5 (VB)	6 (VIB)	7 (VIIB)	8 (VIII)	9 (VIII)	10 (VIII)	11 (IB)	12 (IIB)	13 (IIIA)	14 (IVA)	15 (VA)	16 (VIA)	17 (VIIA)	18 (VIIIA)
Hydrogen 1 H_1 -259.34° -252.87° -240.18° +1-1 1.00794 91.0%																	Helium 2 He_2 -272.2° -268.93° -267.96° 0 4.002602 8.9%
Lithium 2 1 Li_3 180.5° 1342° +1 6.941 1.86×10^{-7}%	Beryllium 2 2 Be_4 1287° 2471° +2 9.012182 2.38×10^{-8}%											Boron 2 3 B_5 2075° 4000° +3 10.811 6.9×10^{-6}%	Carbon 2 4 C_6 4492° 3642° +2+4-4 12.0107 0.033%	Nitrogen 2 5 N_7 -210.00° -195.79° -146.94° ±1±2±3+4+5 14.00674 0.0102%	Oxygen 2 6 O_8 -218.79° -182.95° -118.56° -2 15.9994 0.078%	Fluorine 2 7 F_9 -219.62° -188.12° -129.02° -1 18.9984032 2.7×10^{-6}%	Neon 2 8 Ne_{10} -248.59° -246.08° -228.7° 0 20.1797 0.0112%
Sodium 2 8 1 Na_{11} 97.80° 883° +1 22.989770 0.000187%	Magnesium 2 8 2 Mg_{12} 650° 1090° +2 24.3050 0.00350%											Aluminum 2 8 3 Al_{13} 660.32° 2519° +3 26.981538 0.000277%	Silicon 2 8 4 Si_{14} 1414° 3265° +2+4-4 28.0855 0.00326%	Phosphorus 2 8 5 P_{15} 44.15° 280.5° 721° +3+5-3 30.973761 0.000034%	Sulfur 2 8 6 S_{16} 115.21° 444.60° 1041° +4+6-2 32.066 0.00168%	Chlorine 2 8 7 Cl_{17} -101.5° -34.04° 143.8° +1+5+7-1 35.4527 0.000017%	Argon 2 8 8 Ar_{18} -189.35° -185.85° -122.28° 0 39.948 0.000329%
Potassium 2 8 8 1 K_{19} 63.38° 759° +1 39.0983 0.0000123%	Calcium 2 8 8 2 Ca_{20} 842° 1484° +2 40.078 0.000199%	Scandium 2 8 9 2 Sc_{21} 1541° 2836° +3 44.955910 1.12×10^{-7}%	Titanium 2 8 10 2 Ti_{22} 1668° 3287° +2+3+4 47.867 7.8×10^{-6}%	Vanadium 2 8 11 2 V_{23} 1910° 3407° +2+3+4+5 50.9415 9.6×10^{-7}%	Chromium 2 8 13 1 Cr_{24} 1907° 2671° +2+3+6 51.9961 0.000044%	Manganese 2 8 13 2 Mn_{25} 1246° 2061° +2+3+4+7 54.938049 0.000031%	Iron 2 8 14 2 Fe_{26} 1538° 2861° +2+3 55.845 0.00294%	Cobalt 2 8 15 2 Co_{27} 1495° 2927° +2+3 58.933200 7.3×10^{-8}%	Nickel 2 8 16 2 Ni_{28} 1455° 2913° +2+3 58.6934 0.000161%	Copper 2 8 18 1 Cu_{29} 1084.62° 2562° +1+2 63.546 1.70×10^{-6}%	Zinc 2 8 18 2 Zn_{30} 419.53° 907° +2 65.39 4.11×10^{-6}%	Gallium 2 8 18 3 Ga_{31} 29.76° 2204° +3 69.723 1.23×10^{-7}%	Germanium 2 8 18 4 Ge_{32} 938.25° 2833° +2+4 72.61 3.9×10^{-7}%	Arsenic 2 8 18 5 As_{33} 817° 614s° 1400° +3+5-3 74.92160 2.1×10^{-6}%	Selenium 2 8 18 6 Se_{34} 221° 685° 1493° +4+6-2 78.96 2.03×10^{-7}%	Bromine 2 8 18 7 Br_{35} -7.2° 58.8° 315° +1+5-1 79.904 3.8×10^{-6}%	Krypton 2 8 18 8 Kr_{36} -157.36° 153.22° -63.74° 0 83.80 1.5×10^{-7}%
Rubidium 2 8 18 8 1 Rb_{37} 39.31° 688° +1 85.4678 2.31×10^{-6}%	Strontium 2 8 18 8 2 Sr_{38} 777° 1382° +2 87.62 7.7×10^{-6}%	Yttrium 2 8 18 9 2 Y_{39} 1522° 3345° +3 88.90585 1.51×10^{-6}%	Zirconium 2 8 18 10 2 Zr_{40} 1855° 4409° +4 91.224 3.72×10^{-6}%	Niobium 2 8 18 12 1 Nb_{41} 2477° 4744° +3+5 92.90638 2.28×10^{-6}%	Molybdenum 2 8 18 13 1 Mo_{42} 2623° 4639° +6 95.94 8.3×10^{-6}%	Technetium 2 8 18 13 2 Tc_{43} 2157° 4265° +4+6+7 [98]	Ruthenium 2 8 18 15 1 Ru_{44} 2334° 4150° +3 101.07 6.1×10^{-6}%	Rhodium 2 8 18 16 1 Rh_{45} 1964° 3695° +3 102.90550 1.12×10^{-6}%	Palladium 2 8 18 18 0 Pd_{46} 1554.9° 2963° +2+4 106.42 4.5×10^{-6}%	Silver 2 8 18 18 1 Ag_{47} 961.78° 2162° +1 107.8682 1.58×10^{-6}%	Cadmium 2 8 18 18 2 Cd_{48} 321.07° 767° +2 112.411 5.3×10^{-6}%	Indium 2 8 18 18 3 In_{49} 156.60° 2072° +3 114.818 6.0×10^{-10}%	Tin 2 8 18 18 4 Sn_{50} 231.93° 2602° +2+4 118.710 1.25×10^{-5}%	Antimony 2 8 18 18 5 Sb_{51} 630.63° 1587° +3+5-3 121.760 1.01×10^{-6}%	Tellurium 2 8 18 18 6 Te_{52} 449.51° 988° +4+6-2 127.60 1.57×10^{-6}%	Iodine 2 8 18 18 7 I_{53} 113.7° 184.4° 546° +1+5+7-1 126.90447 2.9×10^{-6}%	Xenon 2 8 18 18 8 Xe_{54} -111.75° -108.04° 16.58° 0 131.29 1.5×10^{-8}%
Cesium 2 8 18 18 8 1 Cs_{55} 28.44° 671° +1 132.90545 1.21×10^{-6}%	Barium 2 8 18 18 8 2 Ba_{56} 727° 1897° +2 137.327 1.46×10^{-6}%	Lanthanum 2 8 18 18 9 2 La_{57} † 918° 3464° +3 138.9055 1.45×10^{-6}%	Hafnium 2 8 18 32 10 2 Hf_{72} 2233° 4603° +4 178.49 5.02×10^{-10}%	Tantalum 2 8 18 32 11 2 Ta_{73} 3017° 5458° +5 180.9479 6.75×10^{-11}%	Tungsten 2 8 18 32 12 2 W_{74} 3422° 5555° +6 183.84 4.34×10^{-10}%	Rhenium 2 8 18 32 13 2 Re_{75} 3186° 5596° +4+6+7 186.207 1.69×10^{-10}%	Osmium 2 8 18 32 14 2 Os_{76} 3033° 5012° +3+4 190.23 2.20×10^{-6}%	Iridium 2 8 18 32 15 2 Ir_{77} 2446° 4428° +3+4 192.217 2.16×10^{-6}%	Platinum 2 8 18 32 16 2 Pt_{78} 1768.4° 3825° +2+4 195.078 4.4×10^{-6}%	Gold 2 8 18 32 18 1 Au_{79} 1064.18° 2856° +1+3 196.96655 6.1×10^{-10}%	Mercury 2 8 18 32 18 2 Hg_{80} -38.83° 356.73° 1477° +1+2 200.59 1.11×10^{-6}%	Thallium 2 8 18 32 18 3 Tl_{81} 304° 1473° +1+3 204.3833 6.0×10^{-10}%	Lead 2 8 18 32 18 4 Pb_{82} 327.46° 1749° +2+4 207.2 1.03×10^{-5}%	Bismuth 2 8 18 32 18 5 Bi_{83} 271.40° 1564° +3+5 208.98038 4.7×10^{-10}%	Polonium 2 8 18 32 18 6 Po_{84} 254° 962° +2+4 [209]	Astatine 2 8 18 32 18 7 At_{85} 302° [210]	Radon 2 8 18 32 18 8 Rn_{86} -71° -61.7° 104° 0 [222]
Francium 2 8 18 32 18 8 1 Fr_{87} 27° +1 [223]	Radium 2 8 18 32 18 8 2 Ra_{88} 700° +2 [226]	Actinium 2 8 18 32 18 9 2 Ac_{89} ‡ 1051° 3198° +3 [227]	Rutherfordium 2 8 18 32 32 10 2 Rf_{104} +4 [261]	Dubnium 2 8 18 32 32 11 2 Db_{105} [262]	Seaborgium 2 8 18 32 32 12 2 Sg_{106} [266]	Bohrium 2 8 18 32 32 13 2 Bh_{107} [264]	Hassium 2 8 18 32 32 14 2 Hs_{108} [269]	Meitnerium 2 8 18 32 32 15 2 Mt_{109} [268]	Element-110 2 8 18 32 32 16 2 110_{110} [271]	Element-111 2 8 18 32 32 17 2 111_{111} [272]	Element-112 2 8 18 32 32 18 2 112_{112} [277]		Element-114 2 8 18 32 32 20 2 114_{114} [289]		Element-116 2 8 18 32 32 22 2 116_{116} [289]		Element-118 2 8 18 32 32 24 2 118_{118} [293]

† Lanthanides	Cerium 2 8 18 19 9 2 Ce_{58} 798° 3443° +3+4 140.116 3.70×10^{-6}%	Praseodymium 2 8 18 21 8 2 Pr_{59} 931° 3520° +3 140.90765 5.44×10^{-10}%	Neodymium 2 8 18 22 8 2 Nd_{60} 1021° 3074° +3 144.24 2.70×10^{-6}%	Promethium 2 8 18 23 8 2 Pm_{61} 1042° 3000° +3 [145]	Samarium 2 8 18 24 8 2 Sm_{62} 1074° 1794° +2+3 150.36 8.42×10^{-10}%	Europium 2 8 18 25 8 2 Eu_{63} 822° 1596° +2+3 151.964 3.17×10^{-10}%	Gadolinium 2 8 18 25 9 2 Gd_{64} 1313° 3273° +3 157.25 1.076×10^{-6}%	Terbium 2 8 18 27 8 2 Tb_{65} 1356° 3230° +3 158.92534 1.97×10^{-10}%	Dysprosium 2 8 18 28 8 2 Dy_{66} 1412° 2567° +3 162.50 1.286×10^{-6}%	Holmium 2 8 18 29 8 2 Ho_{67} 1474° 2700° +3 164.93032 2.90×10^{-10}%	Erbium 2 8 18 30 8 2 Er_{68} 1529° 2868° +3 167.26 8.18×10^{-10}%	Thulium 2 8 18 31 8 2 Tm_{69} 1545° 1950° +3 168.93421 1.23×10^{-10}%	Ytterbium 2 8 18 32 8 2 Yb_{70} 819° 1196° +2+3 173.04 8.08×10^{-10}%	Lutetium 2 8 18 32 9 2 Lu_{71} 1663° 3402° +3 174.967 1.197×10^{-10}%
‡ Actinides	Thorium 2 8 18 32 18 10 2 Th_{90} 1750° 4788° +4 232.0381 1.09×10^{-10}%	Protactinium 2 8 18 32 20 9 2 Pa_{91} 1572° +5+4 231.03588	Uranium 2 8 18 32 21 9 2 U_{92} 1135° 4131° +3+4+5+6 238.0289 2.94×10^{-11}%	Neptunium 2 8 18 32 22 9 2 Np_{93} 644° +3+4+5+6 [237]	Plutonium 2 8 18 32 24 8 2 Pu_{94} 640° 3228° +3+4+5+6 [244]	Americium 2 8 18 32 25 8 2 Am_{95} 1176° 2011° +3+4+5+6 [243]	Curium 2 8 18 32 25 9 2 Cm_{96} 1345° +3 [247]	Berkelium 2 8 18 32 27 8 2 Bk_{97} 1050° +3+4 [247]	Californium 2 8 18 32 28 8 2 Cf_{98} 900° +3 [251]	Einsteinium 2 8 18 32 29 8 2 Es_{99} 860° +3 [252]	Fermium 2 8 18 32 30 8 2 Fm_{100} 1527° +3 [257]	Mendelevium 2 8 18 32 31 8 2 Md_{101} 827° +2+3 [258]	Nobelium 2 8 18 32 32 8 2 No_{102} 827° +2+3 [259]	Lawrencium 2 8 18 32 32 9 2 Lr_{103} 1627° +3 [262]

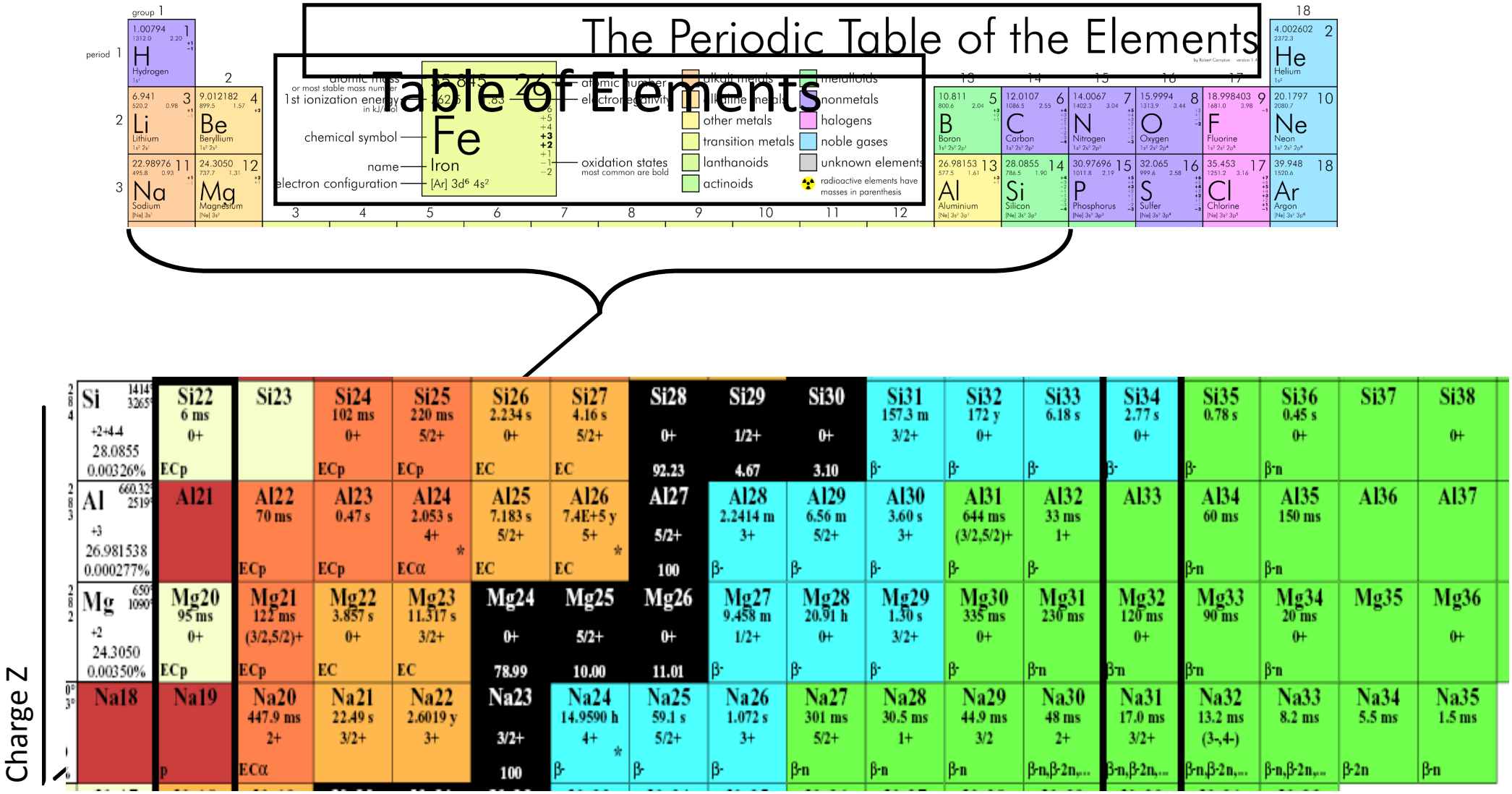
Group

K	Element
L	E_Z
M	M.P.°
N	B.P.°
O	C.P.°
P	Ox.States
Q	At.Weight
	Abundance%

Key to Table

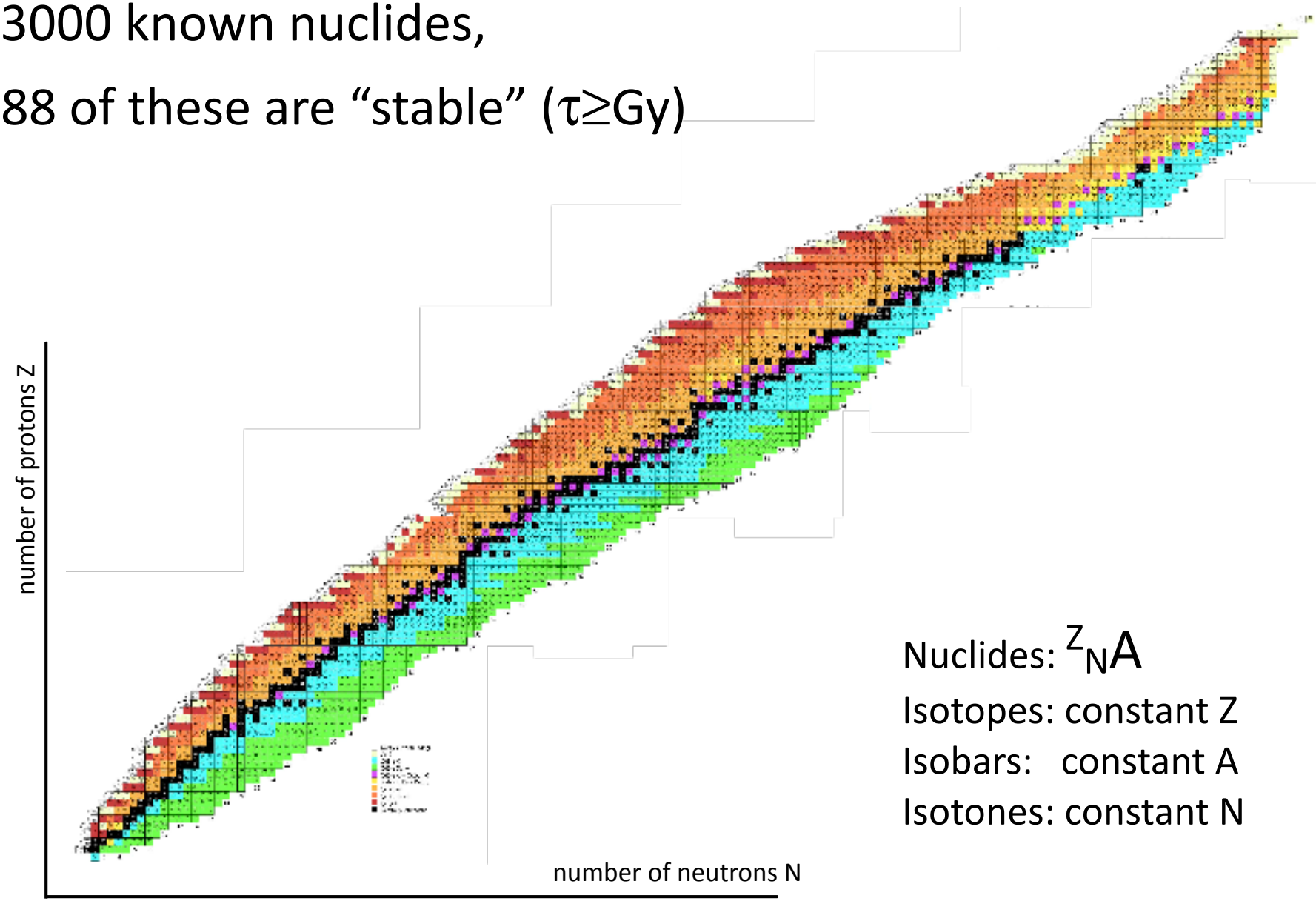
Elements and Isotopes

- Nuclides with same charge but different numbers of nucleons



The Chart of Nuclides

- More than 7000 different nuclides expected to exist
- ~3000 known nuclides,
- 288 of these are “stable” ($\tau \geq$Gy)



Nuclides: ${}^{Z}{}_{N}A$

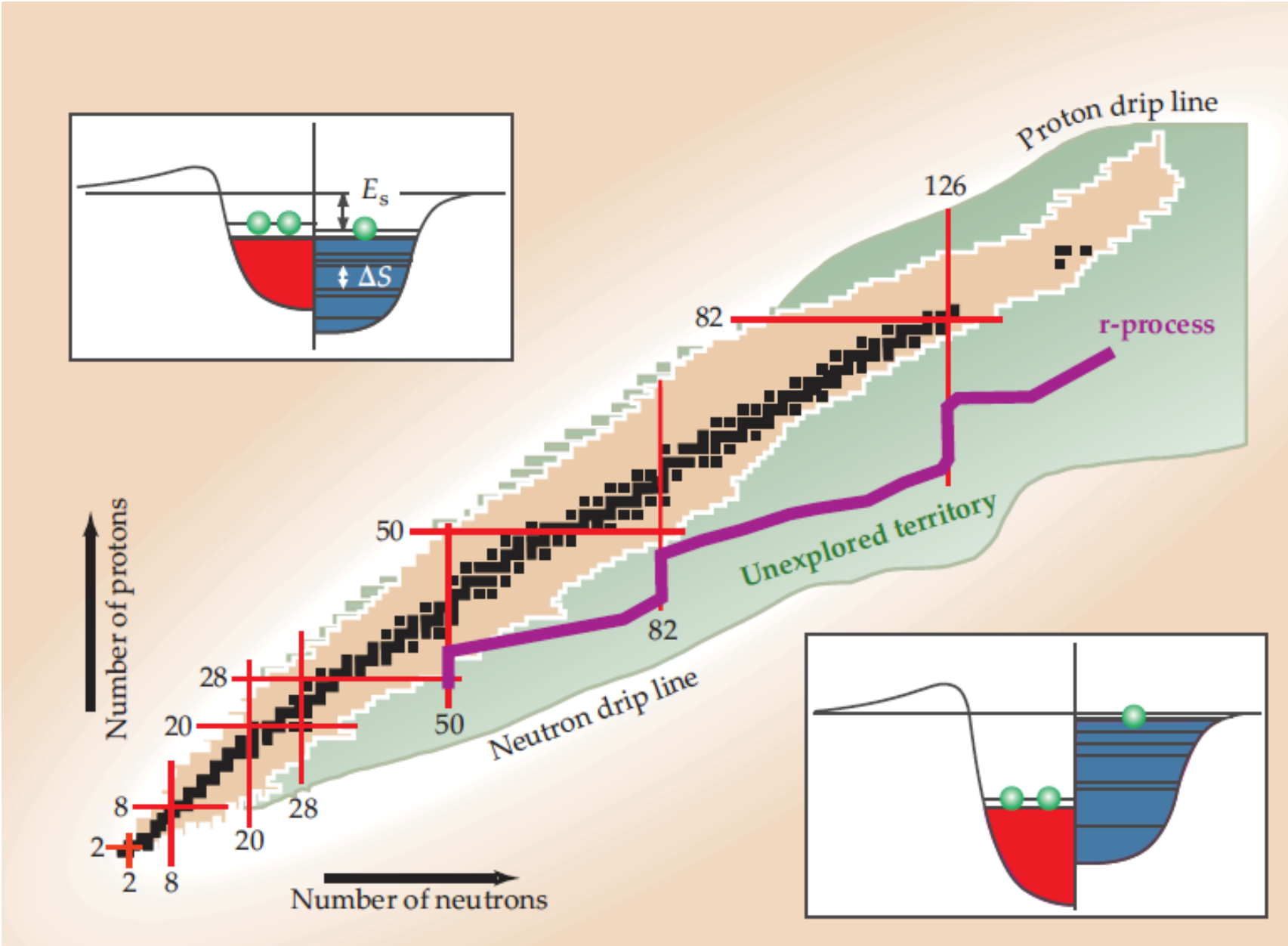
Isotopes: constant Z

Isobars: constant A

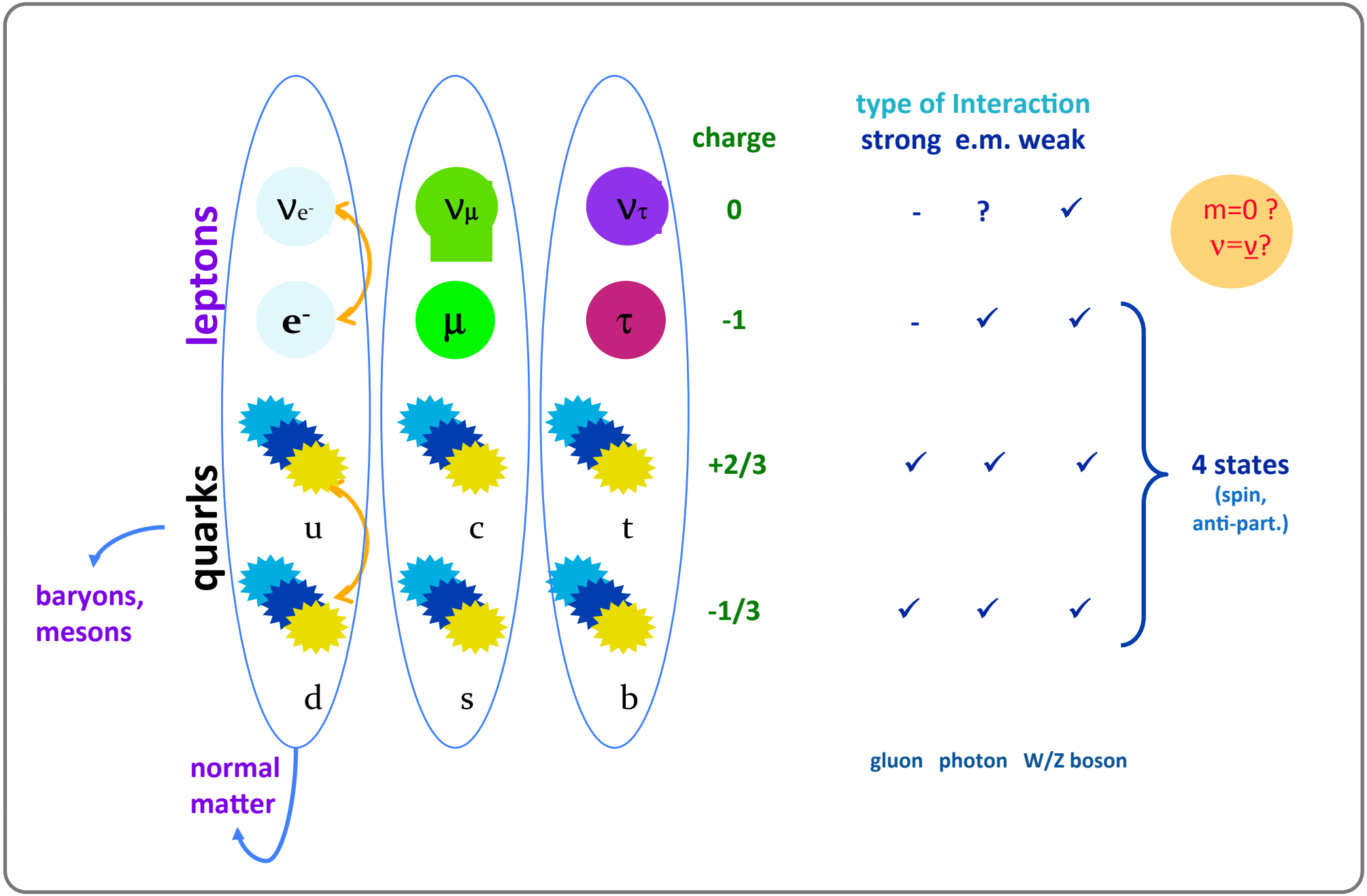
Isotones: constant N

Isotope landscape: Valley of stability

- Nucleon binding by nuclear potential (⇐strong & e.m forces)

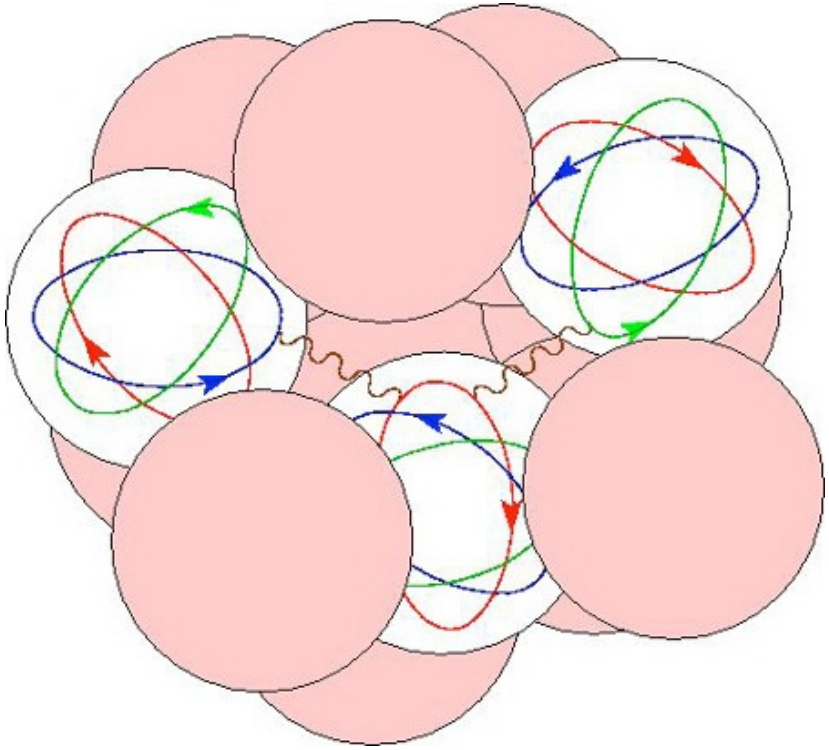


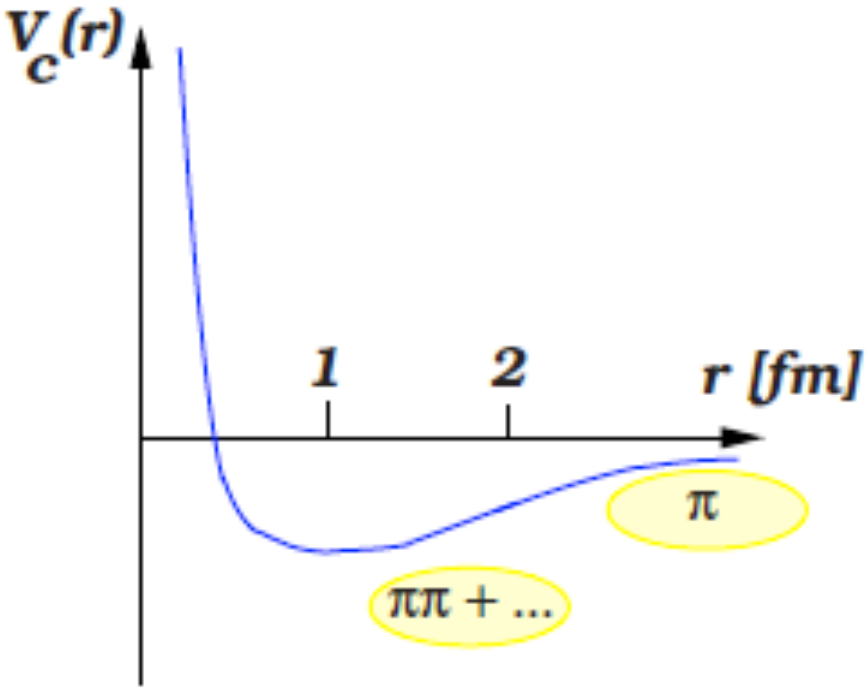
The Standard Model of Particle Physics



The atomic nucleus

- Nuclear binding: from strong force among all nucleons
  - Pion exchanges among quarks mediate the strong interaction

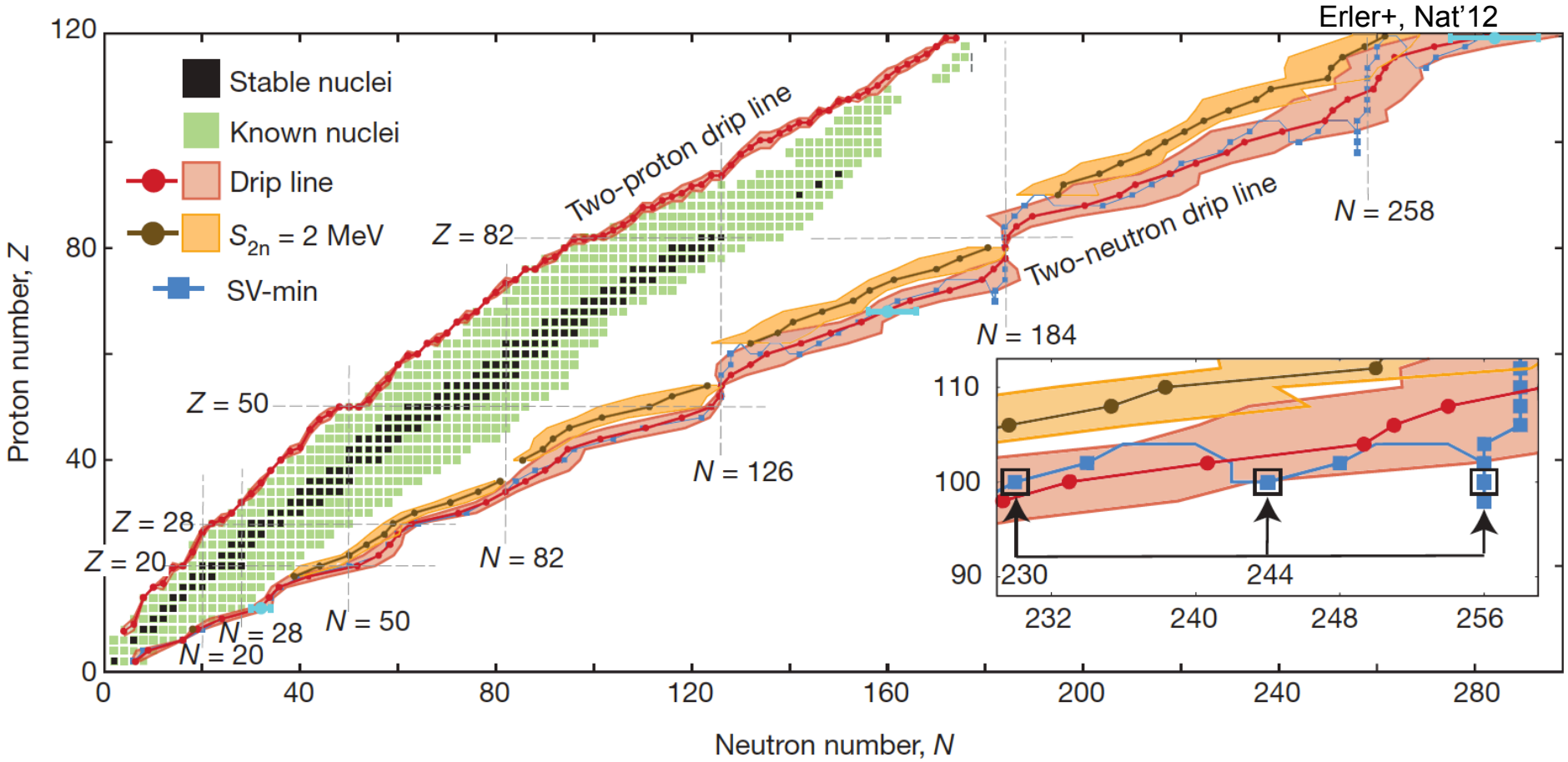




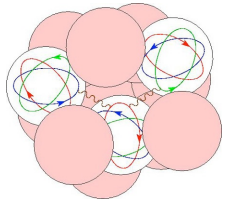
- Effective nuclear-force properties
  - Short range (~few fm)
  - Attractive in intermediate range (fm)
  - Repulsive at small distances (hard core)

Nucleons and nuclei: How large is the phase space

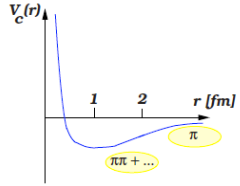
- "Drip" lines: Where nucleon pairs become unbound
  - Depend on details of nuclear structure
    - Shells and their separations, deformation and rotational/vibrational quantizations

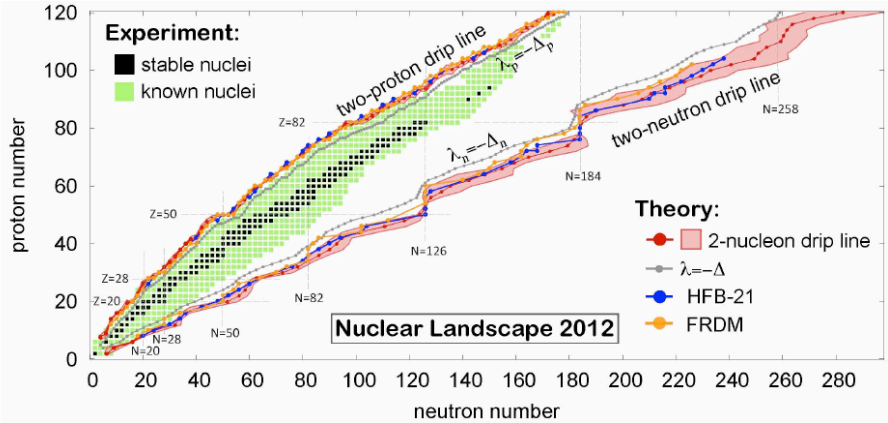


The atomic nucleus: Open questions



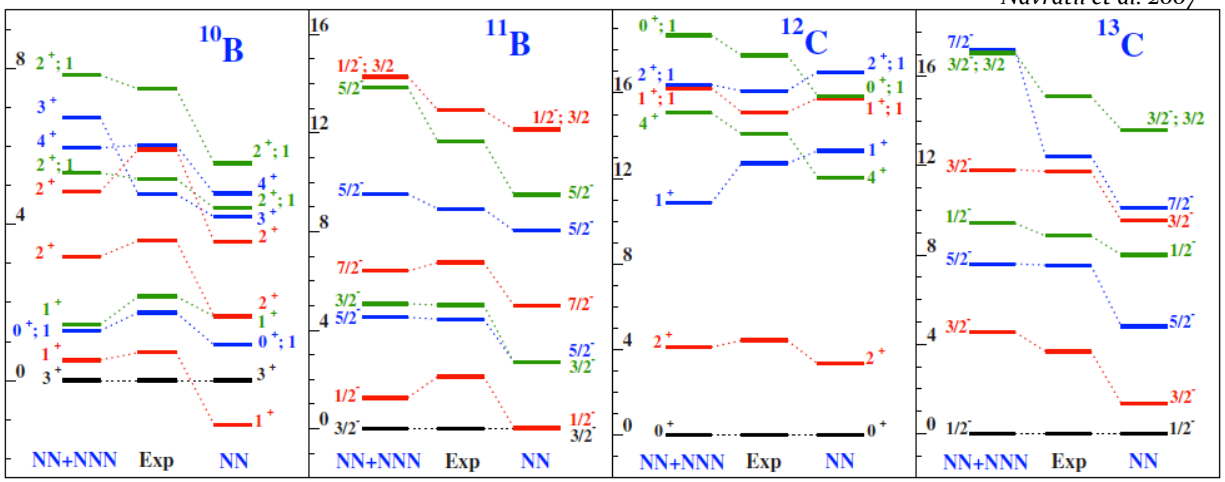
- Nuclear force description is unclear
  - Perturbation theory (e.g. expansions in M_π) not applicable
  - Pion mass of 139 MeV >> Binding energy (~MeV)
  - Gluon momenta >> Binding momentum
  - Multi-pion exchanges important
  - p-n scattering: s-wave scattering
    length 24 fm >> range of potential
  - Drip line inconsistencies

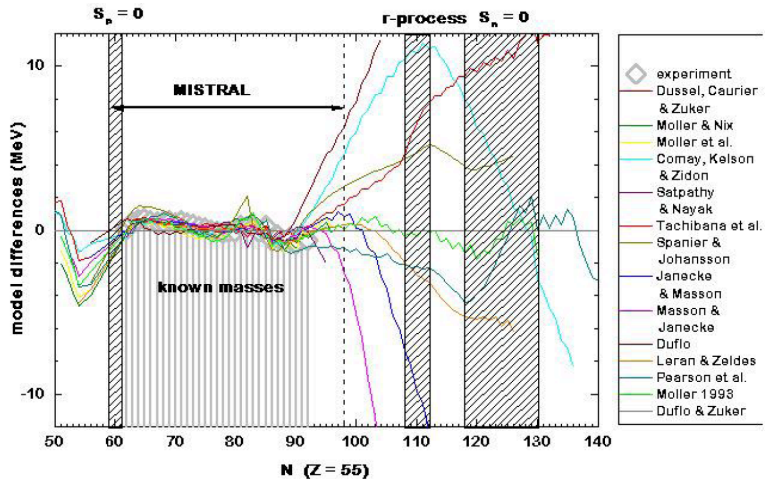




- Models appear incorrect
  - Mass estimates, ab-initio Q.M. of energy levels

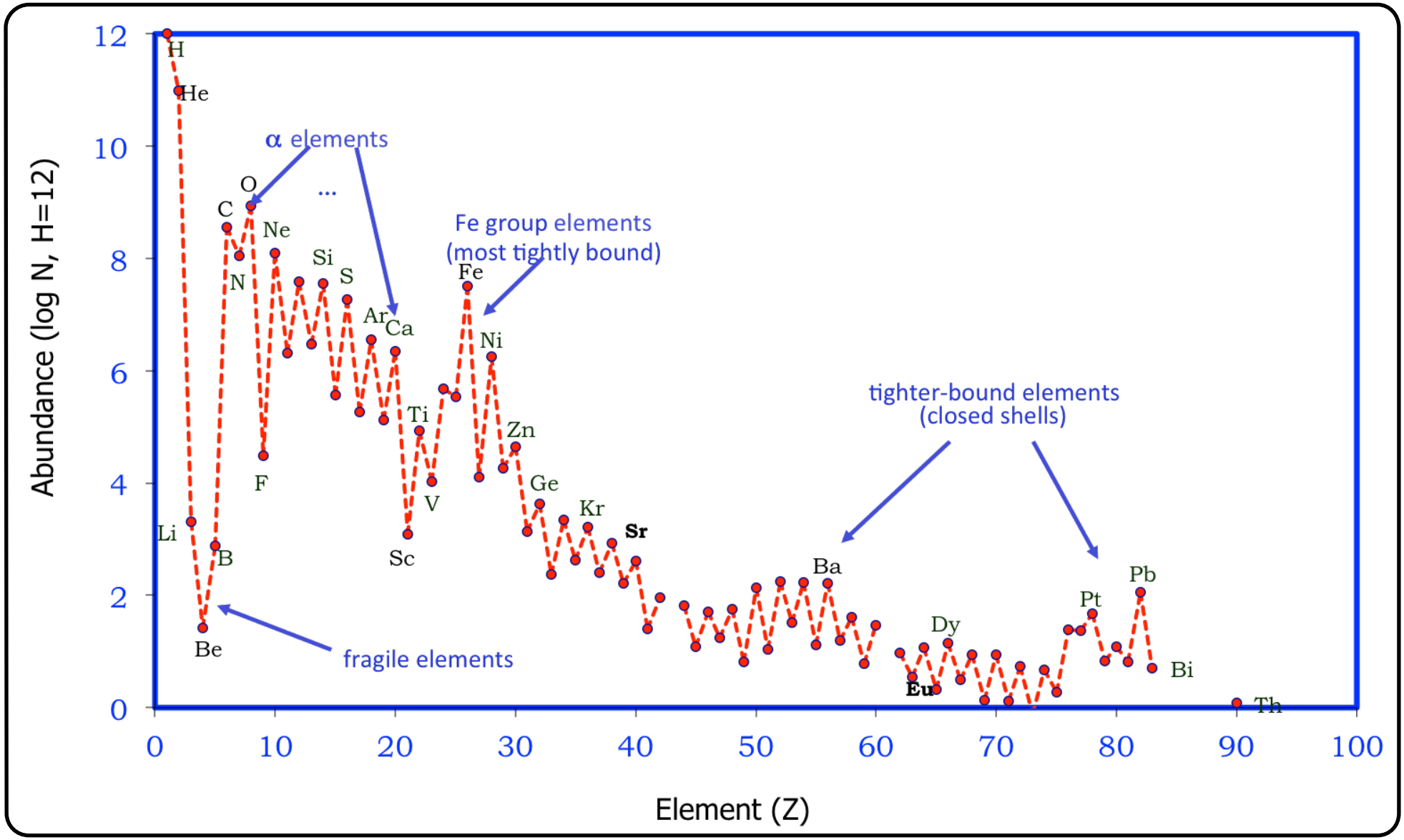
Navratil et al. 2007





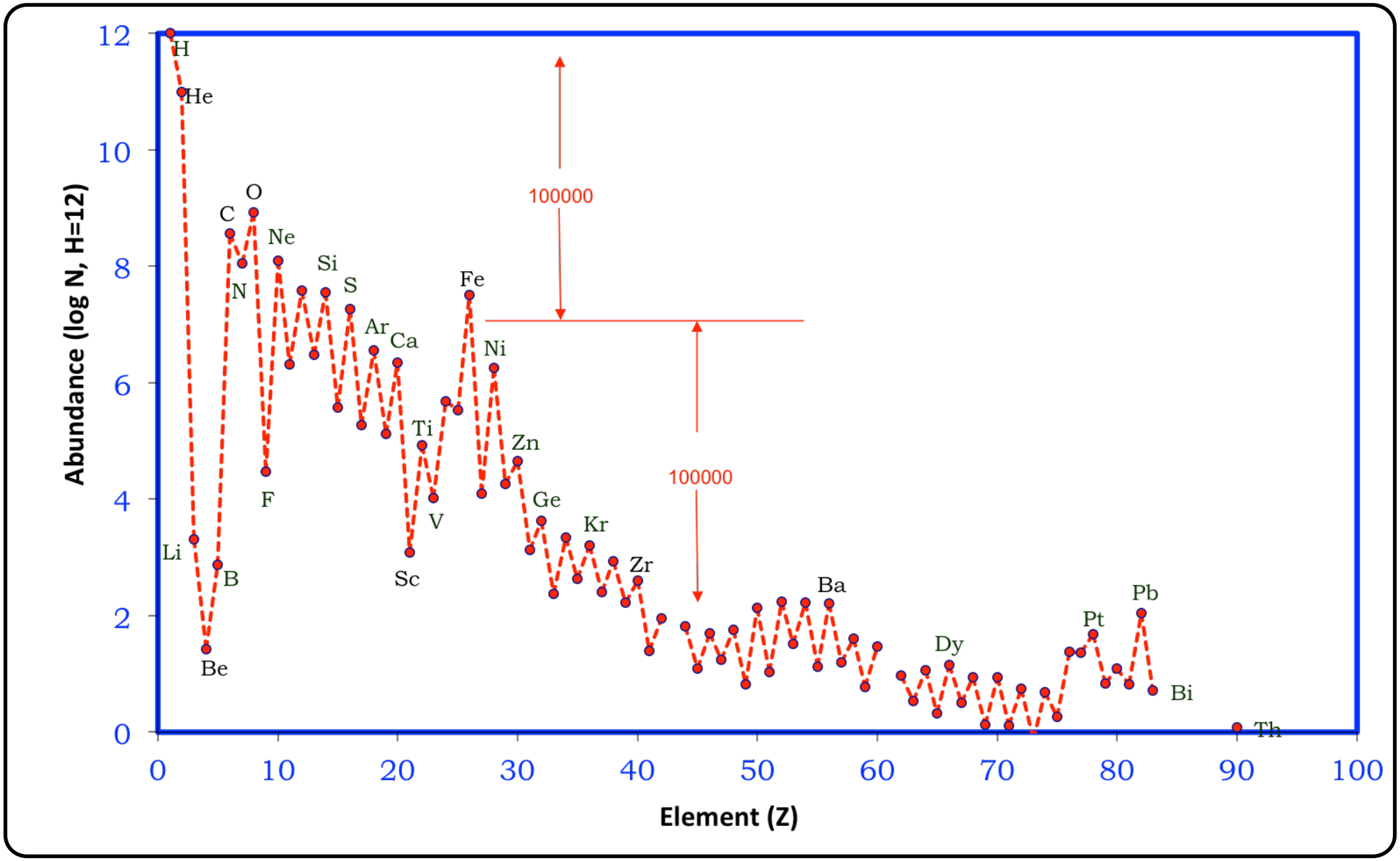
Cosmic elemental abundances

- Signatures of nuclear binding are apparent



Cosmic Abundances and their Evolution

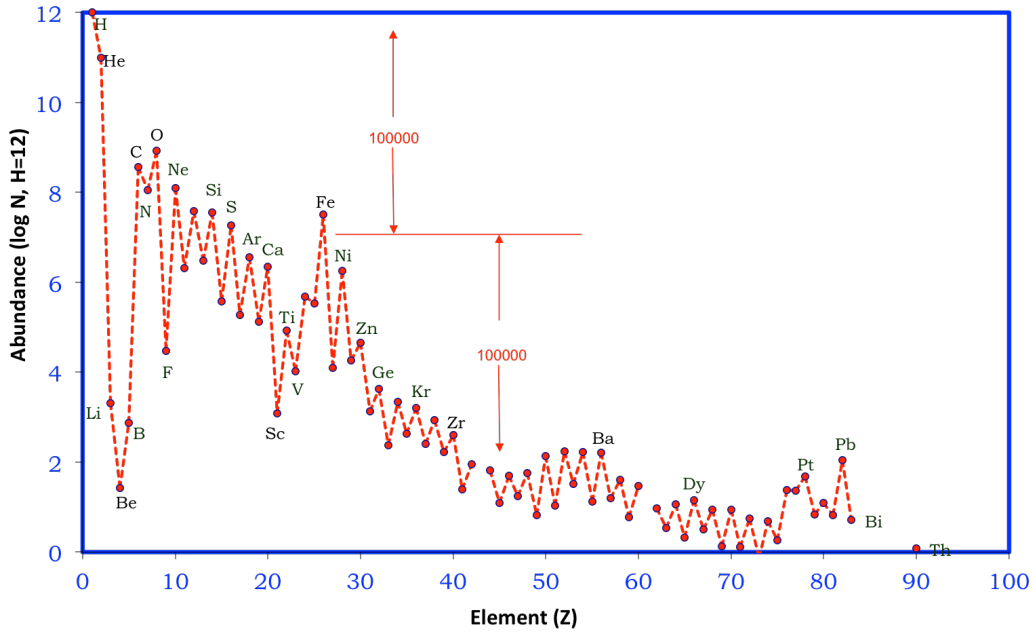
- Abundances extend over 12 orders of magnitude



Measuring Cosmic Elements and Isotopes

- References:
  - Mass standard ^{12}C
  - Mole content = $N_{Avogadro}$

$$Y_i = Y_{{}^{Z}_{N}A} = \frac{X_i}{A_i} = \frac{N_i}{\rho \cdot N_A}$$



  - A well-determined species
    - Hydrogen (astronomical): *log*(N_H).=12
    - Silicon (meteoritic): : *log*(N_{Si}).=6
  - Well-known abundances
    - solar abundances

The Chemical Composition of the Sun *ARAA 2009*

Martin Asplund,[1] Nicolas Grevesse,[2] A. Jacques Sauval,[3] and Pat Scott[4]

$$[Y_i] = \frac{\log\left(Y_{{}^{Z}_{N}A}\right)}{\log\left(Y_{{}^{Z}_{N}A}\right)_\odot}$$

- *Cosmic abundances* *e.g.:*

$$\frac{[Fe]}{[H]} = \frac{\log(Y_{Fe}) / \log(Y_{Fe})_\odot}{\log(Y_H) / \log(Y_H)_\odot}$$

Measuring Cosmic Elements and Isotopes

- Units and References:
  - Number per volume $$N_i = \frac{n_i}{V}\left[\frac{1}{cm^3}\right]$$
  - Avogadro's number and Atomic weight $$W_i[g] = N_A \cdot m_i = N_A \cdot \left[Z_i \cdot m_H + (A_i - Z_i)\cdot m_n + \frac{B_i}{c^2}\right]$$
    $$W_{^{12}C}[g] = 12$$
  - Density $$\rho = \frac{\sum_i N_i A_i}{N_A}$$
  - Nucleonic fraction $$X_i = \frac{N_i \cdot A_i}{\rho \cdot N_A} \qquad \sum_i X_i = 1$$
  - Species fraction $$Y_i = Y_{^Z_N A} = \frac{X_i}{A_i}$$
  - Deviation from solar abundance $$[Y_i] = \frac{\log\left(Y_{^Z_N A}\right)}{\log\left(Y_{^Z_N A}\right)_\odot}$$

Cosmic Abundances and their Evolution

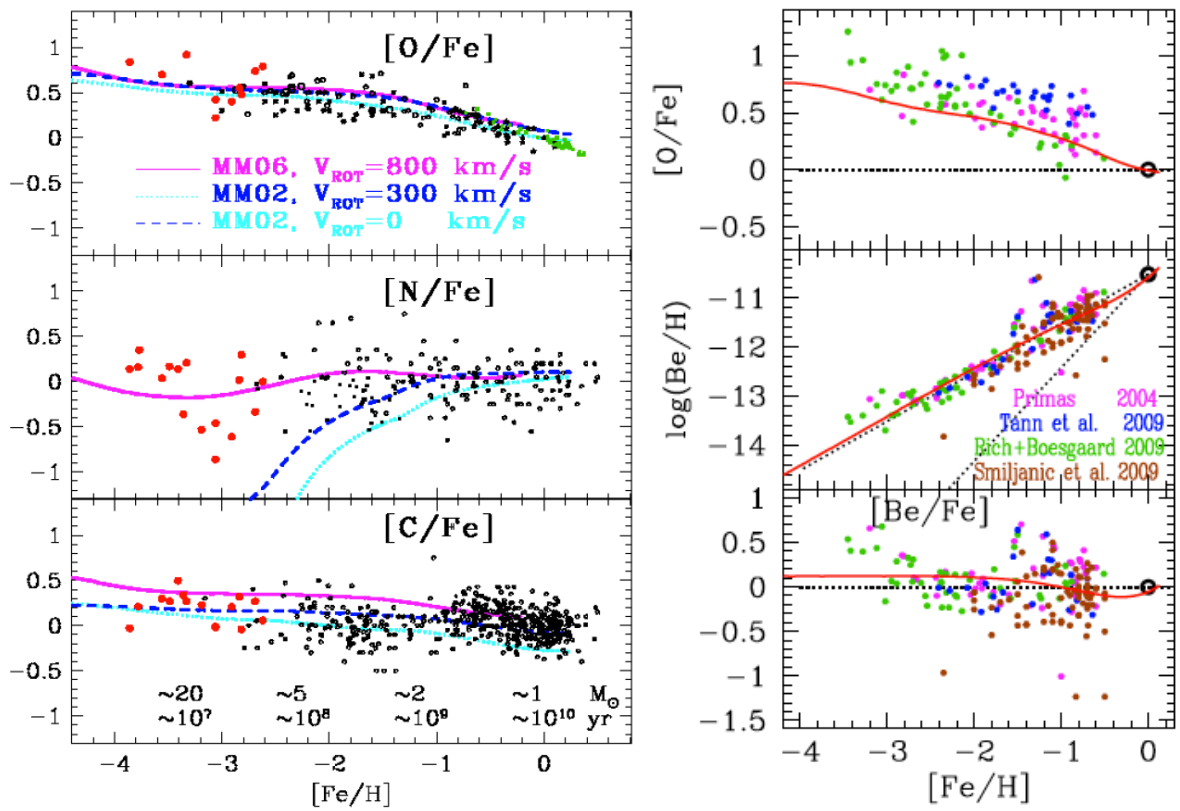
- "Metallicity": Content of all elements heavier than Hydrogen and Helium

- Enrichment with time is plausible. But there is no direct measurement of time
  - Proxies for time:
    - relative Fe abundance
      - can be observed easily in stellar spectra
      - may be biased by variations in dust condensation
    - relative O abundance

Solar abundances *(Lodders+2009)*

Present-Day:	Z/X	X	Y	Z
this work	0.0191	0.7390	0.2469	0.0141
[05A1], [07G]	0.0165	0.7392	0.2486	0.0122
[98G]	0.0231	0.7347	0.2483	0.0169

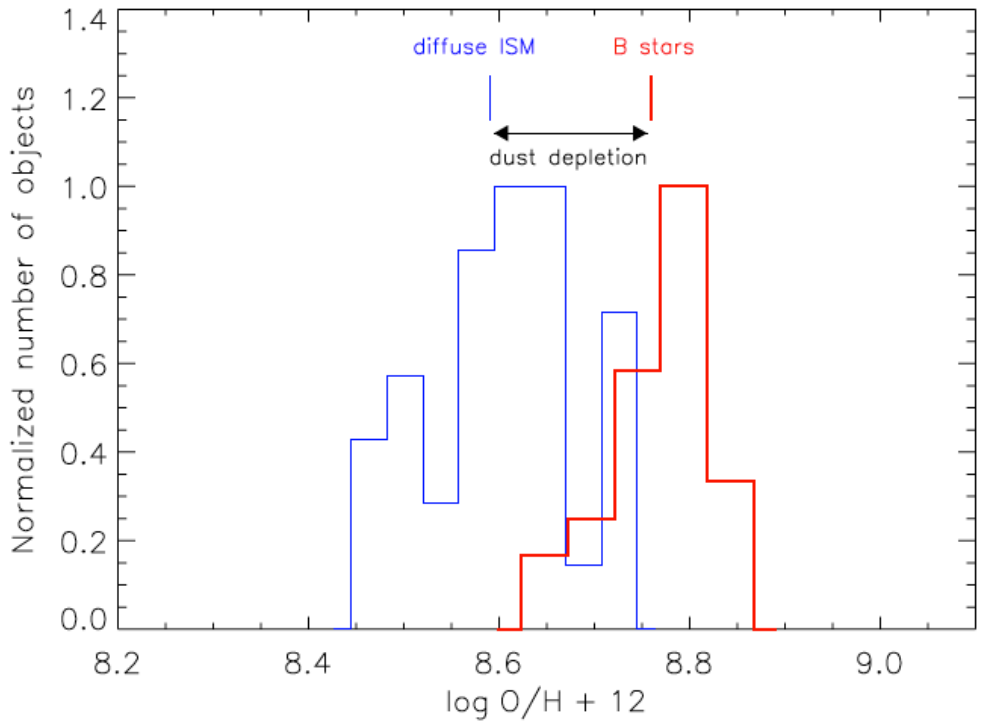
Prantzos+2011

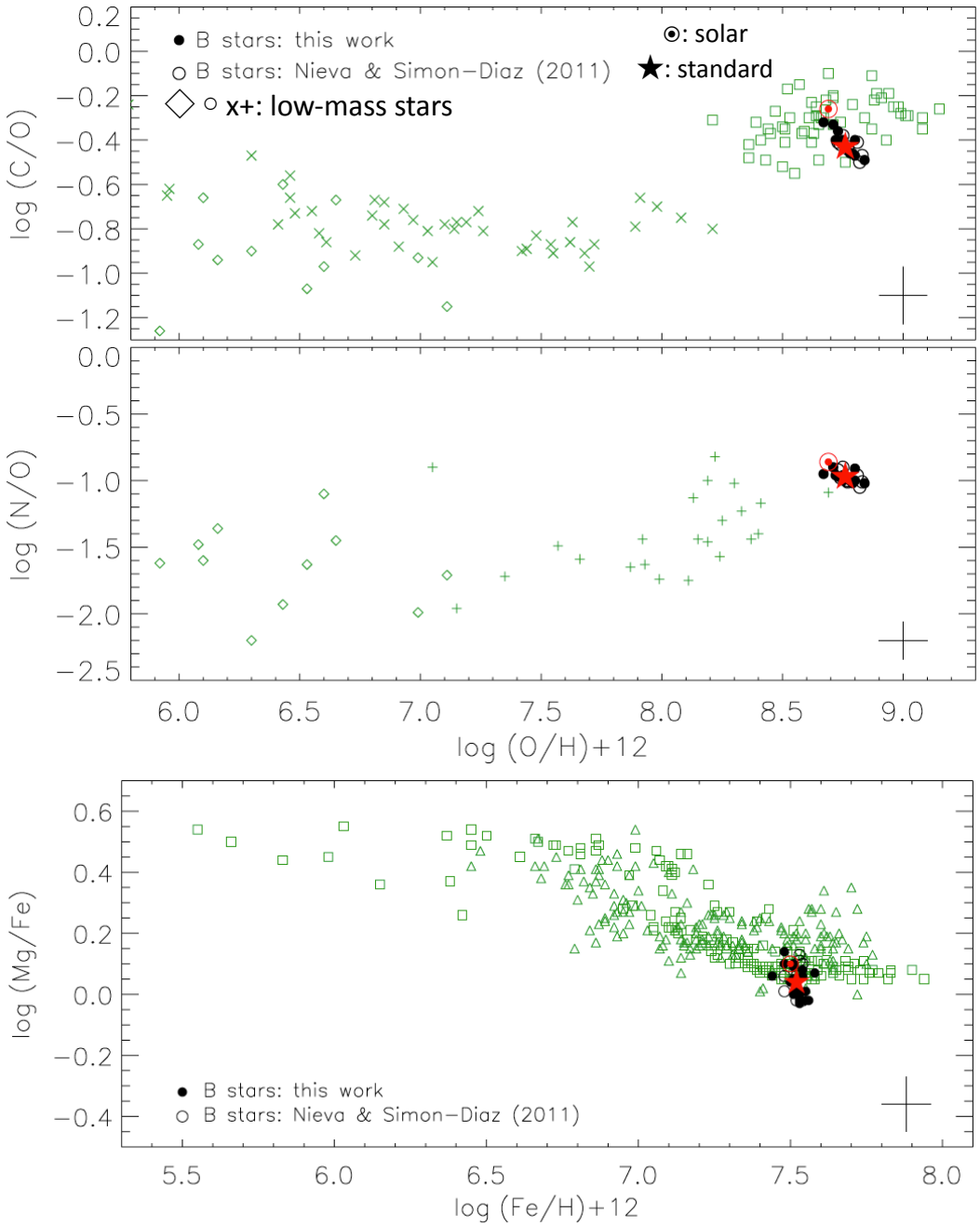


The solar vicinity abundance standard

- Consistency among massive (B) stars and low-mass stars, and with interstellar medium

Nieva&Przybilla+2011





Abundances in the solar vicinity

- Solar vicinity abundances provide a consistent cosmic abundance standard
  - revised approach for stellar abundances, consistency check wrt other abundance proxies *(Nieva & Przybilla 2011)*

Nieva&Przybilla+2011

	Cosmic Standard	Sun – photospheric values		
	B stars – this work	GS98	AGSS09	CLSFB10
X	0.710	0.735	0.7381	0.7321
Y	0.276	0.248	0.2485	0.2526
Z	0.014 ± 0.002	0.017	0.0134	0.0153

- Slight enrichments for the Sun may imply origin at a region inwards in the Galaxy (migration)

Nieva&Przybilla+2011

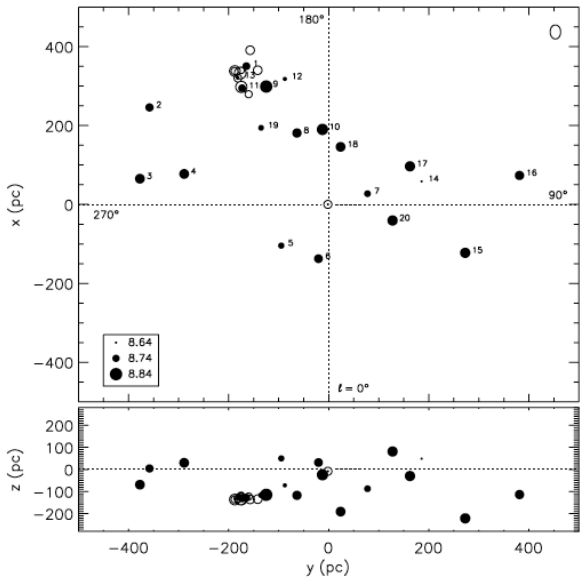


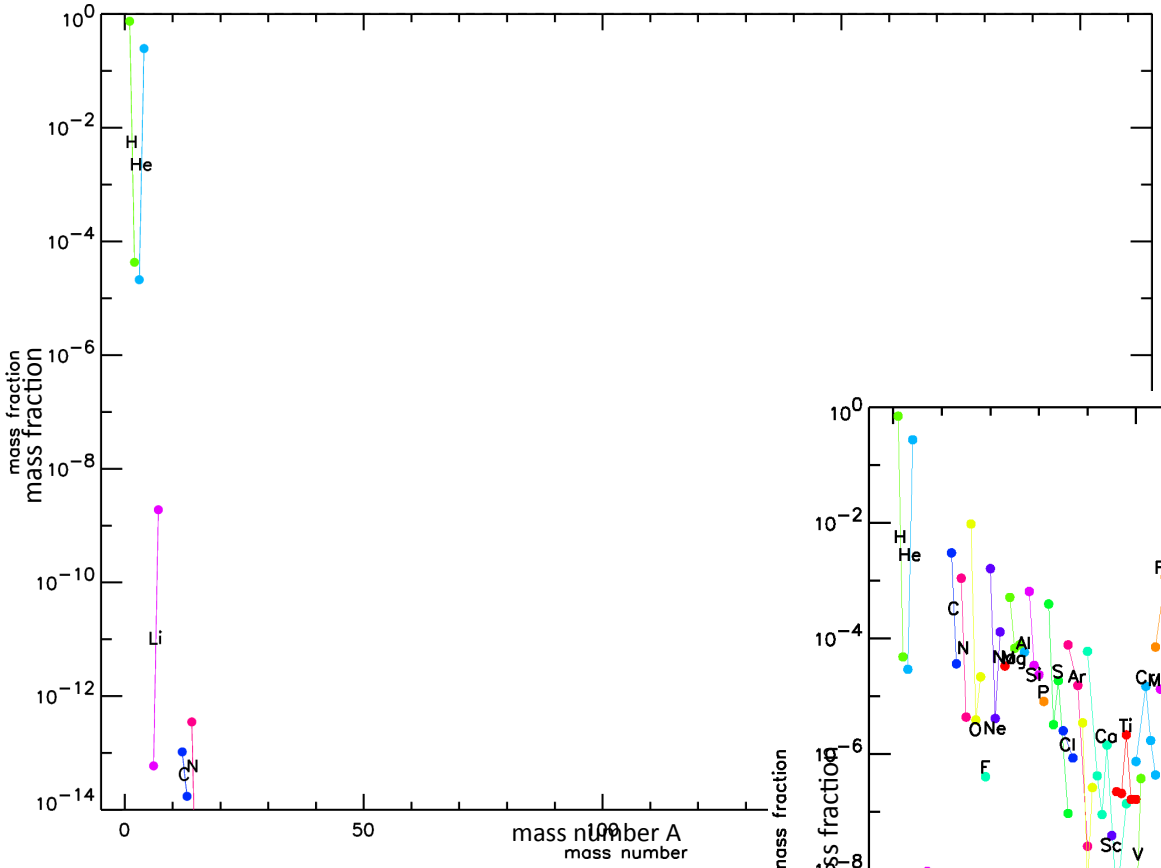
Table 9. Chemical composition of different object classes in the solar neighbourhood.

Elem.	Cosmic Standard B stars – this work[a]		Orion nebula Gas	Orion nebula Dust[d]	Young F&G stars[e]	ISM Gas	ISM Dust[j]	Sun[k] GS98	Sun[k] AGSS09	Sun[k] CLSFB10
He	10.99 ± 0.01	...	10.988 ± 0.003^b	...	...	...	...		10.93 ± 0.01	
C	8.33 ± 0.04	214 ± 20	8.37 ± 0.03^c	~0	8.55 ± 0.10	7.96 ± 0.03^f	123 ± 23	8.52 ± 0.06	8.43 ± 0.05	8.50 ± 0.06
N	7.79 ± 0.04	62 ± 6	7.73 ± 0.09^b	...	...	7.79 ± 0.03^g	0 ± 7	7.92 ± 0.06	7.83 ± 0.05	7.86 ± 0.12
O	8.76 ± 0.05	575 ± 66	8.65 ± 0.03^c	128 ± 73	8.65 ± 0.15	8.59 ± 0.01^h	186 ± 67	8.83 ± 0.06	8.69 ± 0.05	8.76 ± 0.07
Ne	8.09 ± 0.05	123 ± 14	8.05 ± 0.03^c	...	...	...	...	8.08 ± 0.06	7.93 ± 0.10	...
Mg	7.56 ± 0.05	36.3 ± 4.2	$6.50:^c$	33.1 ± 4.2:	7.63 ± 0.17	6.17 ± 0.02^i	34.8 ± 4.2	7.58 ± 0.05	7.60 ± 0.04	...
Si	7.50 ± 0.05	31.6 ± 3.6	6.50 ± 0.25^c	28.4 ± 4.3	7.60 ± 0.14	6.35 ± 0.05^i	29.4 ± 3.6	7.55 ± 0.05	7.51 ± 0.03	...
Fe	7.52 ± 0.03	33.1 ± 2.3	6.0 ± 0.3^c	32.1 ± 2.5	7.45 ± 0.12	5.41 ± 0.04^i	32.9 ± 2.3	7.50 ± 0.05	7.50 ± 0.04	7.52 ± 0.06

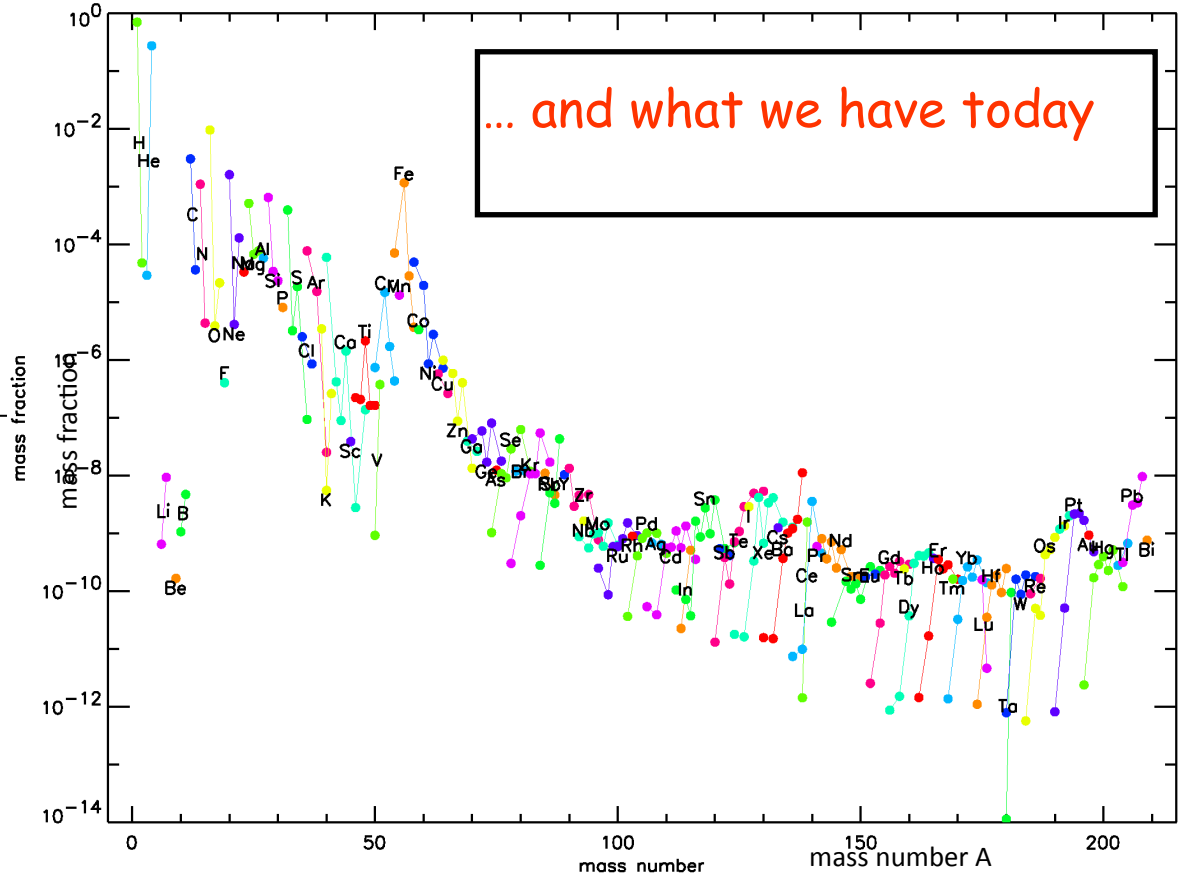
Notes. [a] Including nine stars from Orion (NS11), in units of log(El/H) + 12/ atoms per 10^6 H nuclei – computed from average star abundances (mean values over all individual lines *per element*, equal weight per line), the uncertainty is the standard deviation; [b] Esteban et al. (2004); [c] Simón-Díaz & Stasińska (2011); [d] difference between the cosmic standard and Orion nebula gas-phase abundances, in units of atoms per 10^6 H nuclei; [e] Sofia & Meyer (2001); [f] value determined from strong-line transitions (Sofia et al. 2011), which is compatible with data from the analysis of the [C II] 158 μm emission (Dwek et al. 1997). Weak-line studies of C II] λ2325 Å indicate a higher gas-phase abundance $\varepsilon(C) = 8.11 \pm 0.07$ (Sofia 2004), which corresponds to 84 ± 28 ppm of carbon locked up in dust; [g] Meyer et al. (1997), corrected accordingly to Jensen et al. (2007); [h] Cartledge et al. (2004); [i] Cartledge et al. (2006). The uncertainty in the ISM gas-phase abundances is the standard error of the mean; [j] difference between the cosmic standard and ISM gas-phase abundances, in units of atoms per 10^6 H nuclei; [k] photospheric values of Grevesse & Sauval (1998, GS98), Asplund et al. (2009, AGSS09) and Caffau et al. (2010, CLSFG10).

Evolving cosmic abundances: sources?

what the big bang left behind...



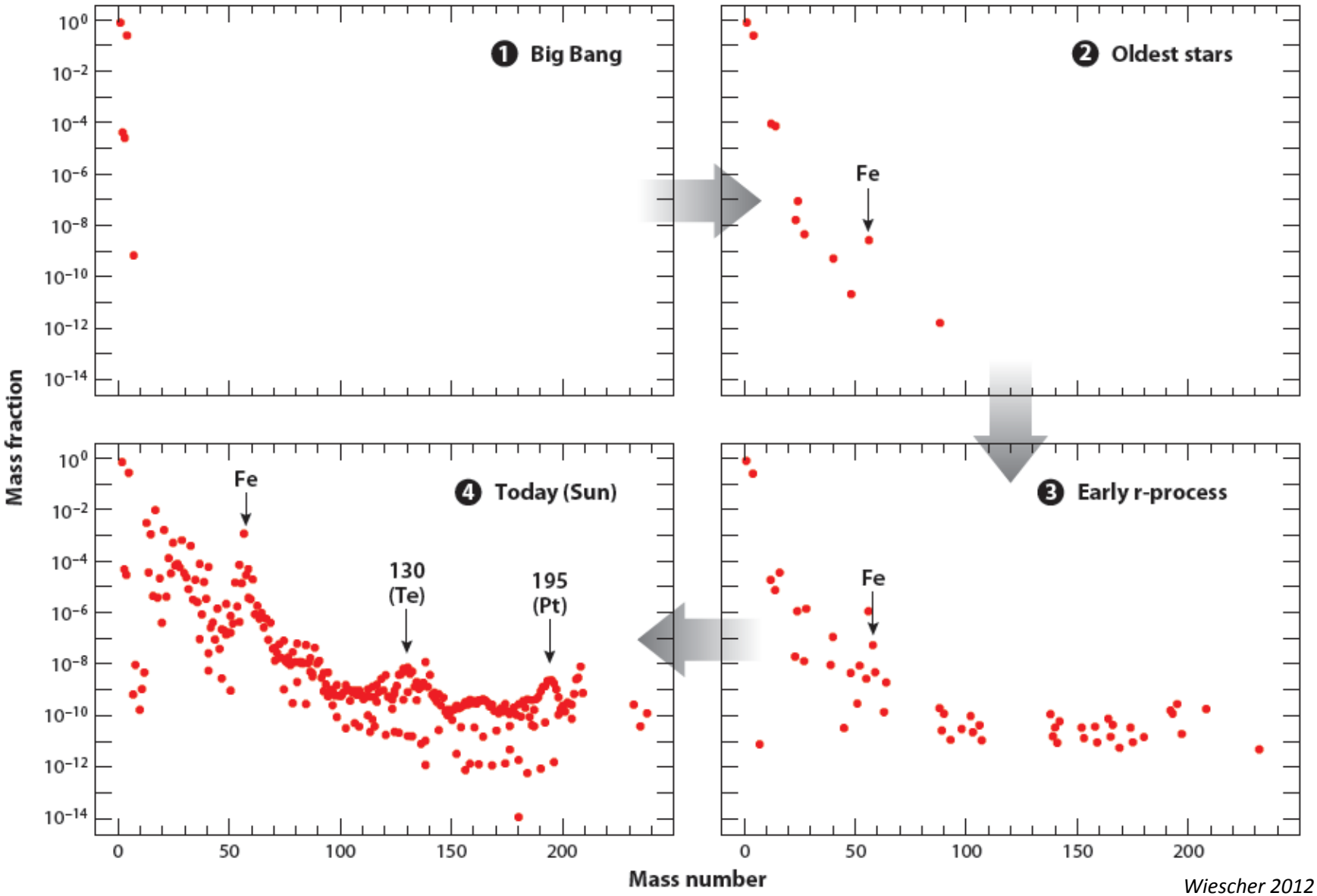
Enrichment of the heavier-element contents of the cosmic gas through nucleosynthesis in stars, supernovae, and ...



what the local universe has now

Steps of Abundance Evolution

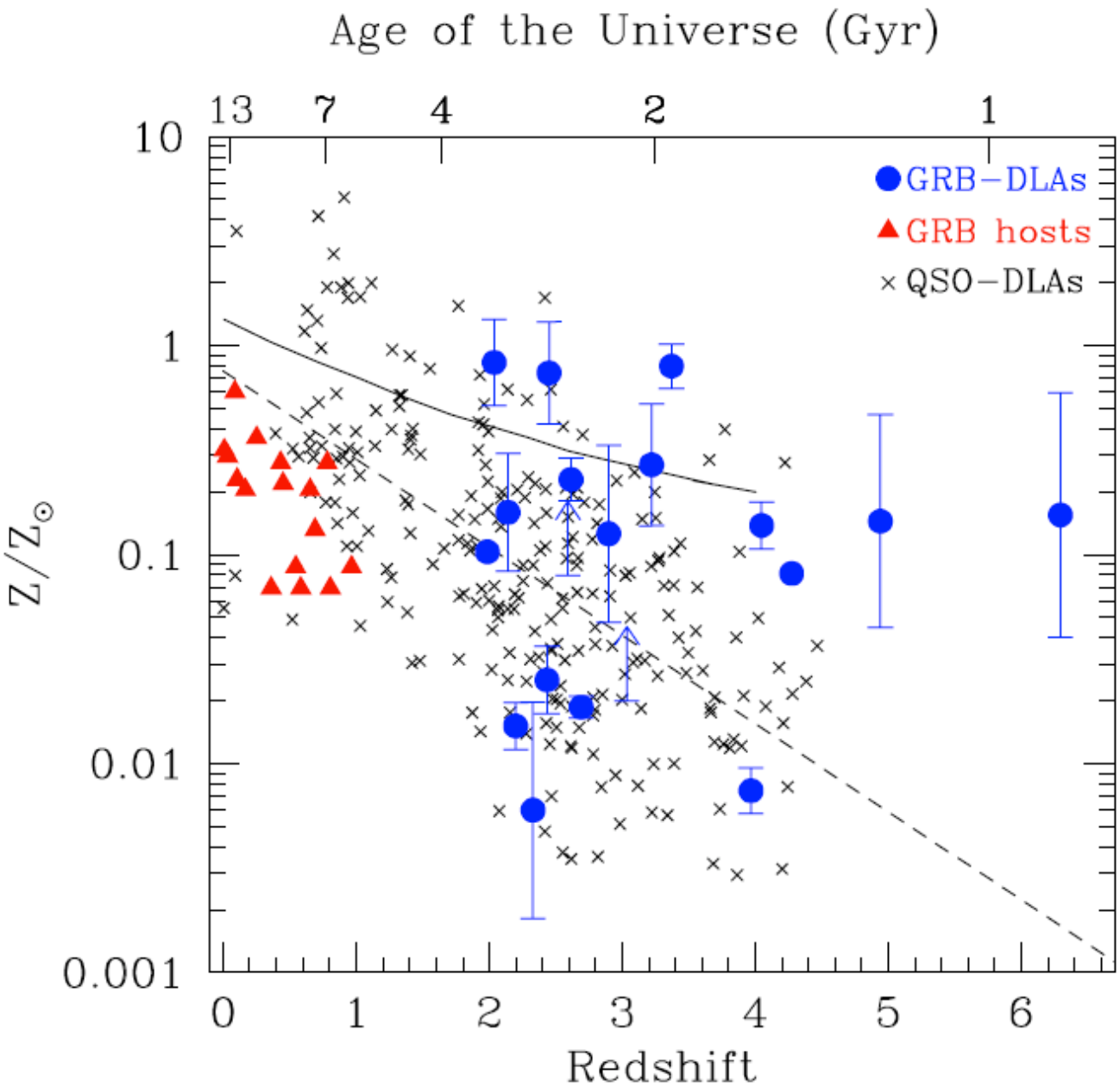
- History cannot be deciphered easily
- Some coarse milestones/phases can be identified



Wiescher 2012

Evolving cosmic abundances: sources?

- Enrichment of the heavier-element contents of the cosmic gas through nucleosynthesis in stars, supernovae, and ...



Evolving cosmic abundances: sources?

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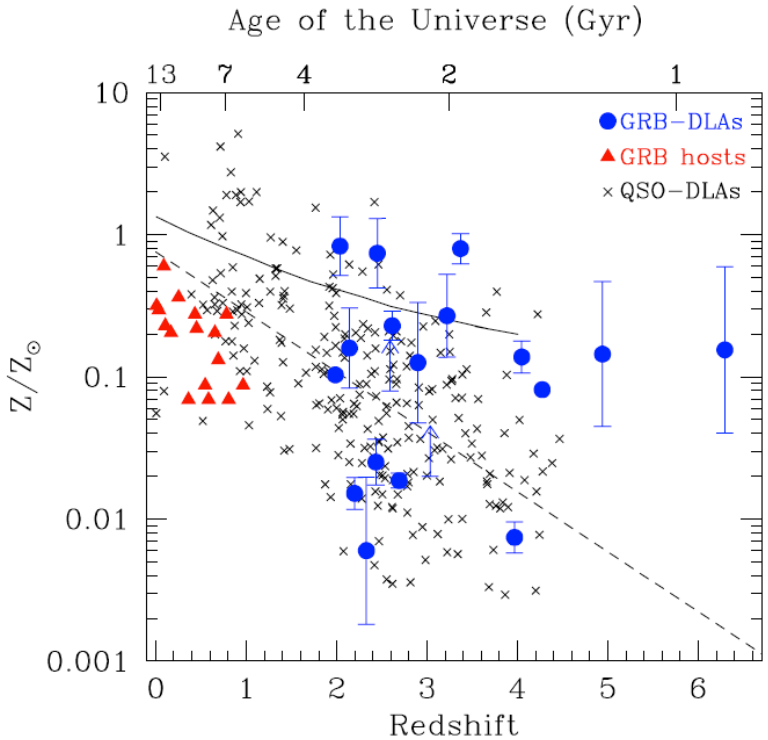
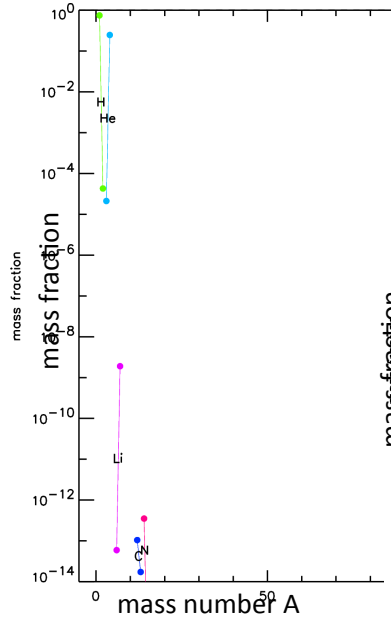
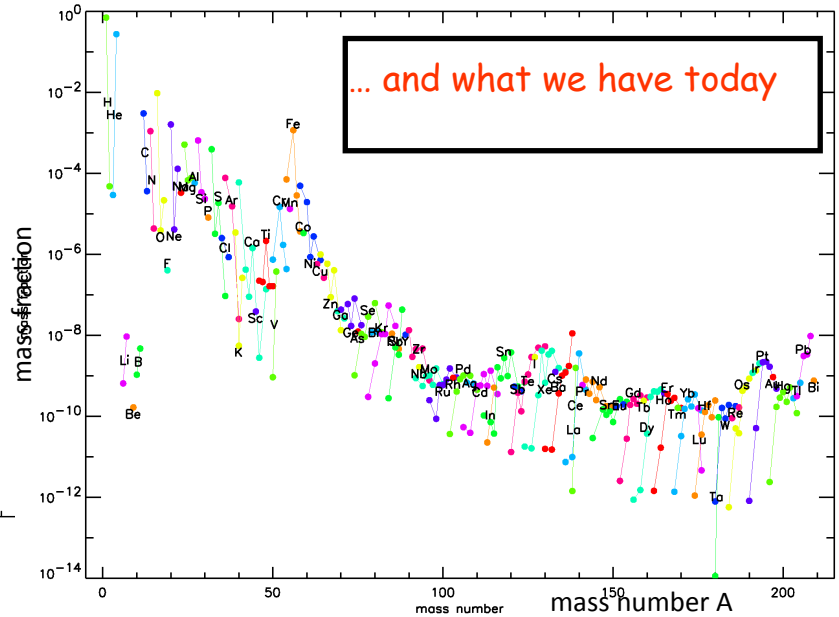


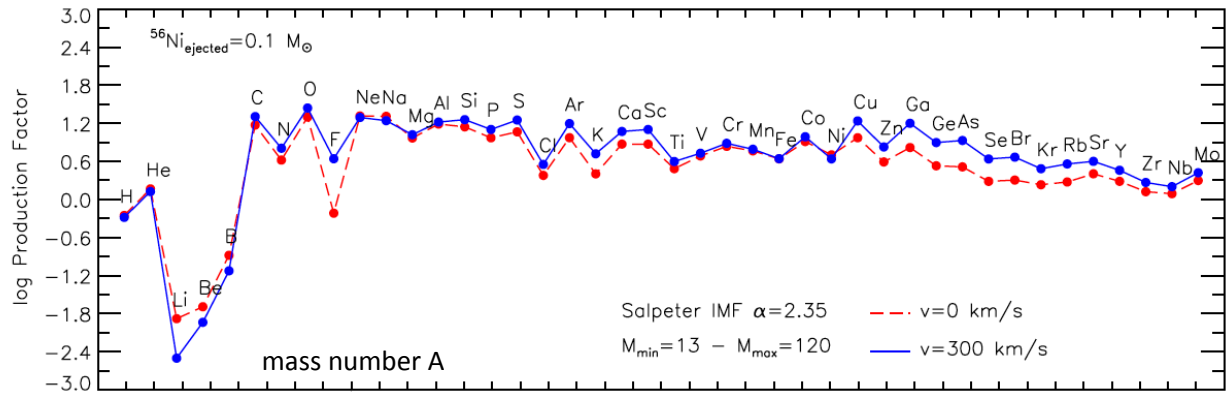
what the big bang left behind...





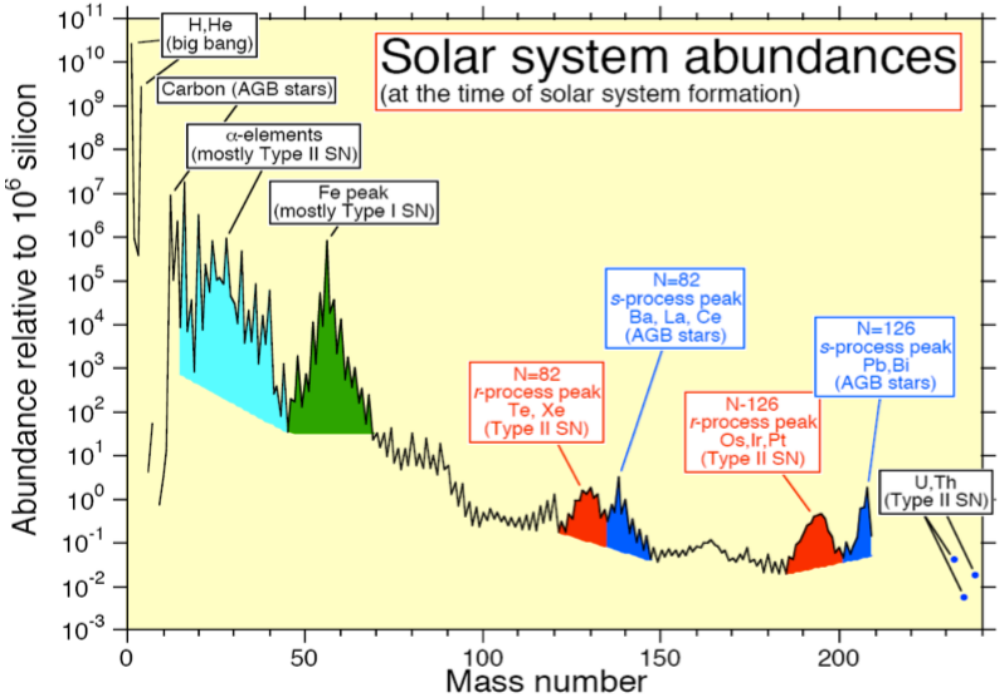
what the local universe has now

production from massive stars

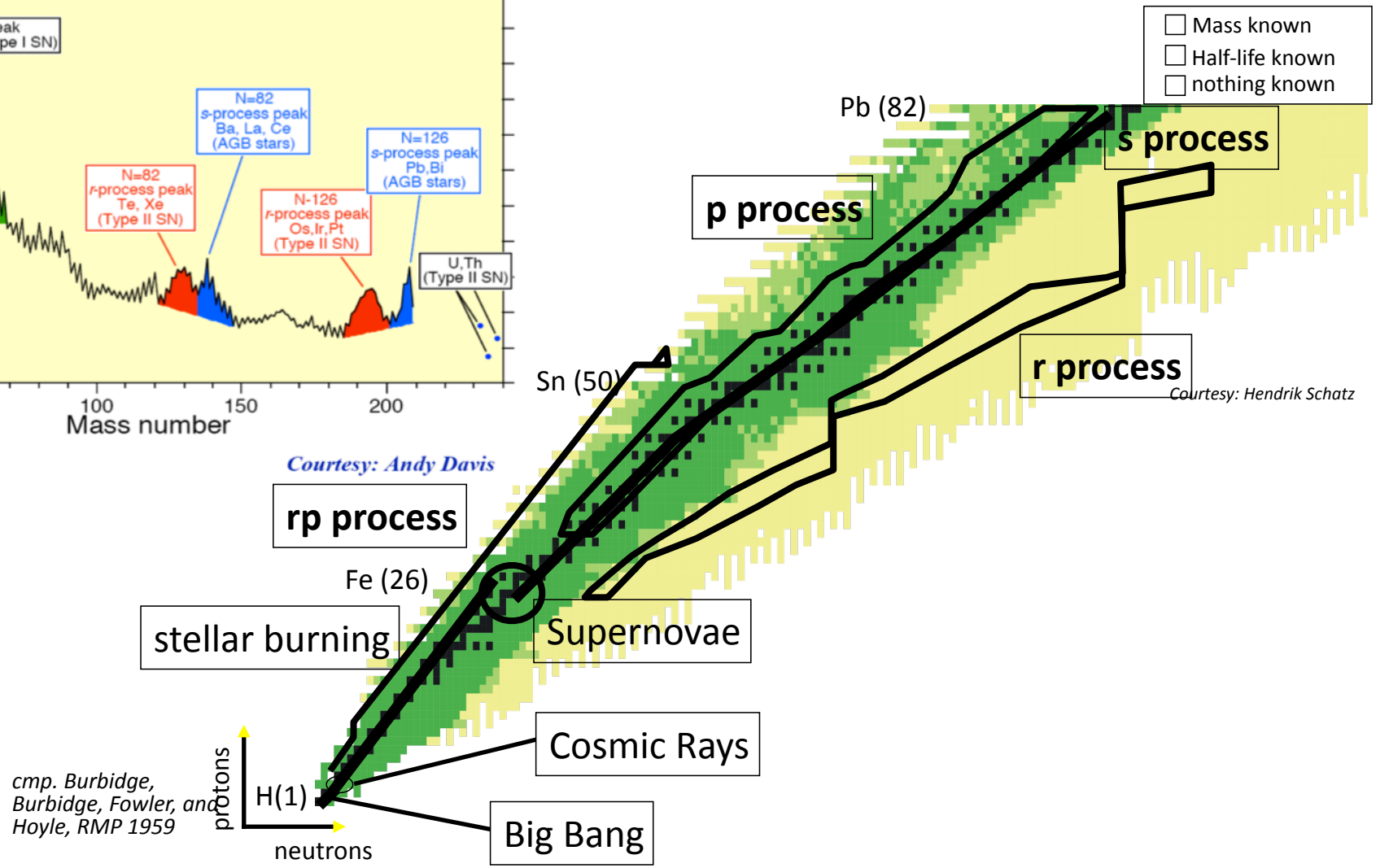


Cosmic origins of the variety of nuclides

- Different "processes" have been associated with nuclide groups



Courtesy: Andy Davis



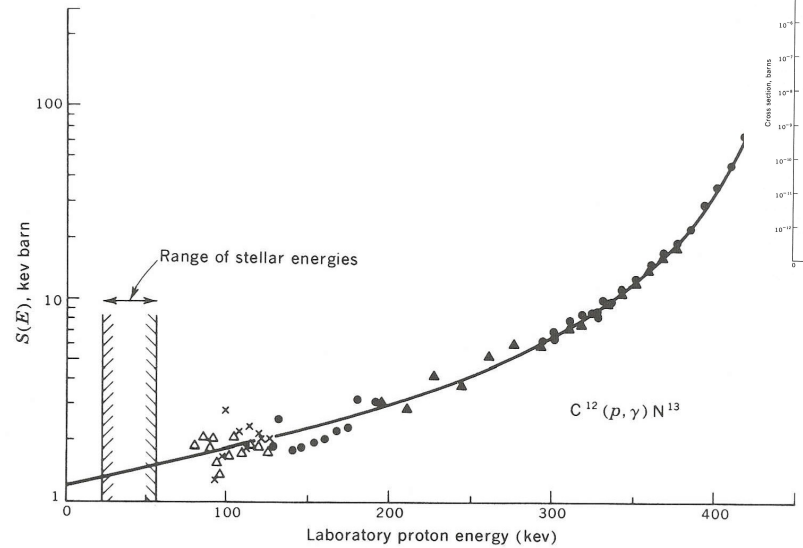
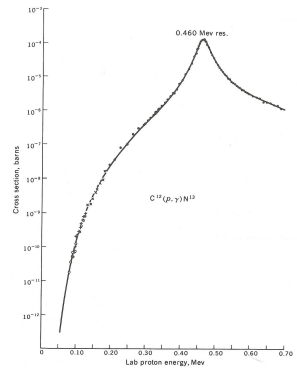
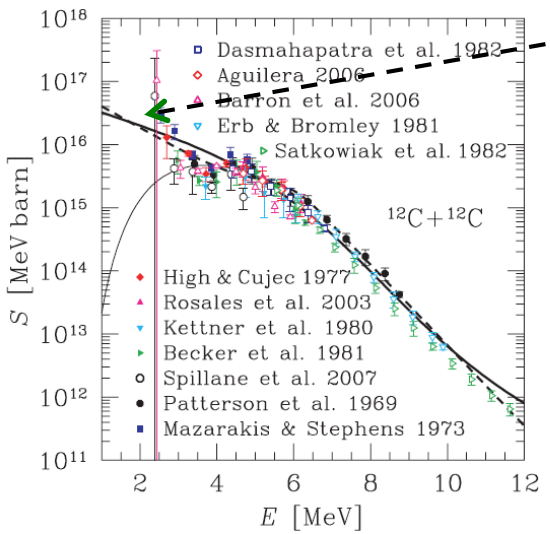
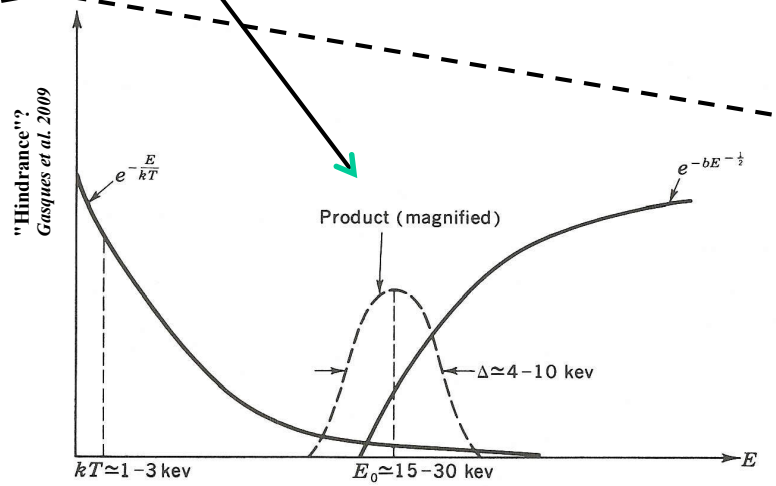
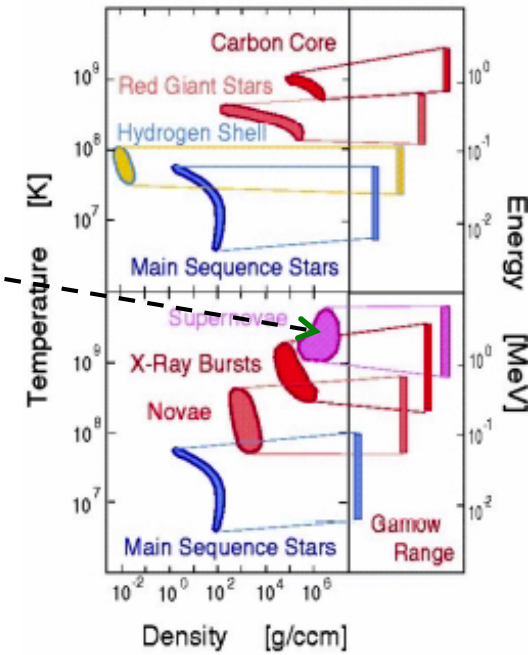
cmp. Burbidge, Burbidge, Fowler, and Hoyle, RMP 1959

Nuclear Reactions in Cosmic Environments

- Tunneling reactions of thermal particle populations
  - Astrophysical S-factor:

$$\sigma(E) = \frac{1}{E} \cdot e^{-2\pi\eta} \cdot S(E)$$

    - isolate nuclear properties from tunneling geometry
  - Gamov peak at ~30 keV

$$\langle \sigma \cdot v \rangle = \left(\frac{8}{\pi \cdot \mu}\right)^{1/2} \cdot \left(\frac{1}{kT}\right)^{3/2} \cdot \int_0^\infty E \cdot \sigma(E) \cdot e^{\frac{-E}{kT}} \cdot dE$$

    - still difficult to measure at nuclear laboratories